PUBLIC ROADS

A JOURNAL OF HIGHWAY RESEARCH

UNITED STATES DEPARTMENT OF AGRICULTURE
BUREAU OF PUBLIC ROADS

VOL. 12, NO. 8 ▽ OCTOBER, 1931

A VIEW OF THE SUBGRADE LABORATORY AT ARLINGTON FARM, VA.

For sale by the Superintendent of Documents, Washington, D. C. - - - - - - - - - - - - - - **See page 2 of cover for price**

PUBLIC ROADS

A JOURNAL OF HIGHWAY RESEARCH

UNITED STATES DEPARTMENT OF AGRICULTURE

BUREAU OF PUBLIC ROADS

CERTIFICATE: By direction of the Secretary of Agriculture, the matter contained herein is published as administrative information and is required for the proper transaction of the public business

The reports of research published in this magazine are necessarily qualified by the conditions of the tests from which the data are obtained. Whenever it is deemed possible to do so, generalizations are drawn from the results of the tests; and, unless this is done the conclusions formulated must be considered as specifically pertinent only to the described conditions

VOL. 12, NO. 8 | OCTOBER, 1931 | G. P. St. CLAIR, Editor

TABLE OF CONTENTS

THE BUREAU OF PUBLIC ROADS

Willard Building, Washington, D. C.

REGIONAL HEADQUARTERS

Mark Sheldon Building, San Francisco, Calif.

DISTRICT OFFICES

DISTRICT No. 1. Oregon, Washington, and Montana.
Post Office Building, P. O. Box 3900, Portland, Oreg.

DISTRICT No. 2. California, Arizona, Nevada, and Hawaii.
Mark Sheldon Building, 461 Market St., San Francisco, Calif.

DISTRICT No. 3. Colorado, New Mexico, and Wyoming.
237 Customhouse, Nineteenth and Stout Sts., Denver, Colo.

DISTRICT No. 4. Minnesota, North Dakota, South Dakota, and Wisconsin.
410 Hamm Building, St. Paul, Minn.

DISTRICT No. 5. Iowa, Kansas, Missouri, and Nebraska.
8th Floor, Saunders-Kennedy Building, Omaha Nebr.

DISTRICT No. 6. Arkansas, Louisiana, Oklahoma, and Texas.
1912 Fort Worth National Bank Building, Fort Worth, Tex.

DISTRICT No. 7. Illinois, Indiana, Kentucky, and Michigan.
South Chicago Post Office Bldg., Chicago, Ill.

DISTRICT No. 8. Alabama, Georgia, Florida, Mississippi, South Carolina, and Tennessee.
Shepherd Building, P. O. Box J, Montgomery, Ala.

DISTRICT No. 9. Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont.
Federal Building, Troy, N. Y.

DISTRICT No. 10. Delaware, Maryland, North Carolina, Ohio, Pennsylvania, Virginia, and West Virginia.
Willard Building, Washington, D. C.

DISTRICT No. 11. Alaska.
Room 419, Federal and Territorial Building, Juneau, Alaska.

DISTRICT No. 12. Idaho and Utah.
403 Fred J. Kiesel Building, Ogden, Utah.

PROCEDURES FOR TESTING SOILS FOR THE DETERMINATION OF THE SUBGRADE SOIL CONSTANTS

By A. M. WINTERMYER, Assistant Highway Engineer, E. A. WILLIS, Assistant Highway Engineer and R. C. THOREEN, Junior Highway Engineer, United States Bureau of Public Roads

THIS is the fourth of a series of articles on the subject of subgrade soils. The reports published in the June and July, 1931, issues of PUBLIC ROADS discussed the soil test constants, their significance, and their application in practice. The report published in the September issue described the procedure for making subgrade soil surveys in the field. The purpose of the present report is to acquaint the reader with the procedure employed in testing soils in the subgrade laboratory of the bureau at Arlington, Va.

PREPARATION OF SAMPLE

1. *Apparatus.*—The apparatus consists of the following:

A balance sensitive to 0.1 gram.

A mortar and rubber-covered pestle suitable for breaking up the aggregations of soil particles.

A series of sieves, of square-mesh wire cloth, conforming to the requirements of the standard specifications for sieves for testing purposes of the American Society for Testing Materials (serial designation E–11). The sizes required are shown in Table 1.

A riffle sampler or sample splitter, for quartering the samples.

TABLE 1.—*Requirements for sieve openings and wire diameters with permissible variations*

Mesh designation, U. S. standard sieve series	Sieve opening		Wire diameter		Tolerance			
					Average opening	Wire diameter		Maximum opening
						Under	Over	
No.	*Millimeters*	*Inches*	*Millimeters*	*Inches*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
4	4.76	0.1870	1.27	0.050	±3	15	30	10
10	2.00	.0787	.76	.0299	±3	15	30	10
40	.42	.0165	.25	.0098	±5	15	30	25
200	.074	.0029	.053	.0021	±8	15	35	60

2. *Sample.*—The soil sample as received from the field is dried thoroughly in the air. A representative test sample of the amount required to perform the desired tests is then selected by the method of quartering or by the use of a sampler. The amounts of material required to perform the individual tests are as follows:

(*a*) For the mechanical analysis, material passing No. 10 sieve is required in amounts equal to 115 grams of sandy soils and 65 grams of either silt or clay soils.

(*b*) For the physical tests, material passing the No. 40 sieve is required in total amount equal to 200 grams, allocated as follows:

	Grams
Liquid limit	30
Plastic limit	15
Centrifuge moisture equivalent	10
Field moisture equivalent	50
Volumetric shrinkage	30
Flocculation and check tests	65

(*c*) Physical tests of binder material are performed only when it is desired to investigate the properties of the active constituents in sand-clay and gravel road-surfacing materials. In this case 100 grams of the material passing the No. 200 sieve are required and the tests are performed in the following order: Field moisture equivalent, plastic limit, liquid limit, volumetric shrinkage, and centrifuge moisture equivalent. The material remaining after the conclusion of each test is used in the next test, except that the test for the centrifuge moisture equivalent is made with material not used in previous tests.

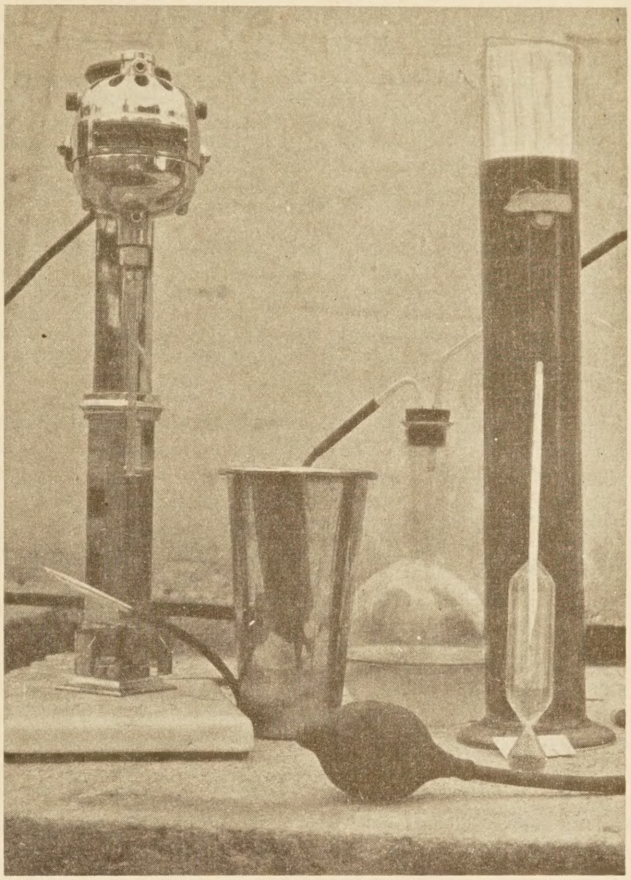

FIGURE 1.—BUOYOUCOS HYDROMETER, CYLINDER, AND SPECIAL MILK-SHAKE MACHINE

3. *Procedure.*—That portion of the air-dried sample selected for test is weighed and the weight recorded as the weight of the total test sample uncorrected for hygroscopic moisture. The test sample is separated by sieving with a No. 10 sieve. That fraction retained on the No. 10 sieve is ground in a mortar with a rubber-covered pestle until the aggregations of soil particles are broken up into the separate grains. The ground soil is then separated into two fractions by sieving with a No. 10 sieve.

That fraction retained after the second sieving is washed free of all fine material, dried, and weighed. This weight is recorded as the weight of coarse material. The coarse material after being washed and dried is sieved on the No. 4 sieve and the weight retained on the No. 4 sieve is recorded.

The fractions passing the No. 10 sieve in both sieving operations are thoroughly mixed together, and by the method of quartering or the use of a sampler a portion weighing approximately 115 grams for sandy soils and approximately 65 grams for silt and clay soils is selected for mechanical analysis.

The remaining portion of the material passing the No. 10 sieve is then separated into two parts by means of a No. 40 sieve. The fraction retained on the No. 40 sieve is discarded. The fraction passing the No. 40 sieve is used for the physical tests.

MECHANICAL ANALYSIS BY COMBINED SIEVE AND HYDROMETER METHOD

1. *Apparatus.*—The apparatus consists of the following:

An analytical balance sensitive to 0.001 gram.

A special milk-shake machine with specially designed dispersion cup.

A hydrometer graduated to read grams of soil per liter of suspension. The milk-shake machine and hydrometer, illustrated in Figure 1, were designed by G. J. Bouyoucos and are described in Soil Science, (vol. 23, No. 4, April, 1927, pp. 319 to 330).

A glass graduate 18 inches high and 2½ inches in diameter and graduated for a volume of 1,000 cubic centimeters.

A Fahrenheit thermometer accurate to 1°.

A series of sieves, of square-mesh wire cloth, conforming to the requirements of the standard specifications for sieves for testing purposes of the American Society for Testing Materials (serial designation E–11). The sieves required are shown in Table 2.

A water bath for maintaining the soil suspension at a constant temperature during the hydrometer analysis. This is an insulated zinc tank and maintains the temperature of the suspension at faucet-water temperature. It is illustrated in Figure 2.

A glass cylinder 9½ inches high and 2 inches in diameter, having a capacity of about 425 cubic centimeters.

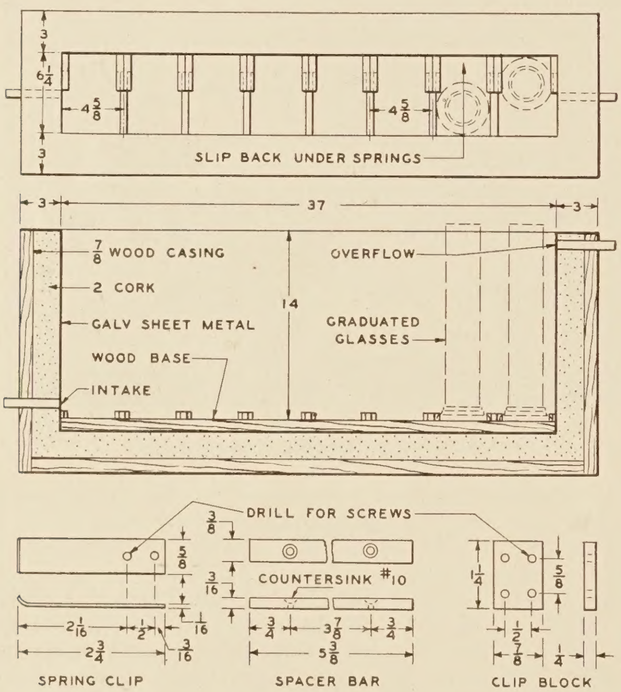

FIGURE 2.—TANK FOR GRADUATED GLASSES, USED FOR MAINTAINING SOIL SUSPENSIONS AT CONSTANT TEMPERATURE DURING HYDROMETER ANALYSIS

2. *Sample.*—Of that portion of the total sample selected for the mechanical analysis, 15 grams are used to determine the hygroscopic moisture and the remainder is used for the combined sieve and hydrometer analysis.

3. *Determination of hygroscopic moisture.*—The 15 grams selected for this purpose are dried to constant weight in an oven at 110° C., weighed, and the results recorded.

4. *Flocculation test.*—Five cubic centimeters of soil particles (weight in grams equal to five times the specific gravity of the soil particles) of that fraction passing the No. 40 sieve are placed in a graduate and vigorously shaken with 45 cubic centimeters of distilled water for two minutes. The graduate is then set aside for a period of 24 hours. If during this period there is evidence of flocculation, the fact is recorded, together with a note regarding the extent of flocculation and the approximate time at which it became evident.

TABLE 2.—*Requirements for sieve openings and wire diameters with permissible variations*

Mesh designation, U. S. standard sieve series	Sieve opening		Wire diameter		Tolerance			
					Average opening	Wire diameter: Under	Wire diameter: Over	Maximum opening
No.	*Millimeters*	*Inches*	*Millimeters*	*Inches*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
20	0.84	0.0331	0.42	0.0165	±5	15	30	25
40	.42	.0165	.25	.0098	±5	15	30	25
60	.25	.0098	.162	.0064	±6	15	35	40
140	.105	.0041	.074	.0029	±8	15	35	60
200	.074	.0029	.053	.0021	±8	15	35	60

5. *Hydrometer test procedure.*—The portion of air-dried soil selected for mechanical analysis is dispersed by one of the three methods described below. The method to be used is determined by the plasticity index of the soil.

A. In the case of soils having a plasticity index between 0 and 5, the soil is placed in the special dispersion cup and distilled water is added until the cup is within 2 inches of being full. A deflocculating agent, 20 cubic centimeters of sodium silicate solution (3° Baumé at 76° F.), is then added and the contents of the cup are mixed by the special milk-shake machine for a period of five minutes.

B. In the case of soils having a plasticity index between 5 and 20 the soil is placed in a small evaporating dish and completely covered with water. It is allowed to soften under water for a period of at least 18 hours. After the soil has softened it is washed into the special dispersion cup and dispersed in the same manner as in method *A*, except that the time of dispersion is increased to 10 minutes.

C. In the case of soils having a plasticity index greater than 20 the soil is placed in a glass cylinder and to this is added 100 cubic centimeters of 6 per cent hydrogen peroxide. The cylinder is shaken until the soil is completely wetted. The cylinder is then covered with a watch glass and placed in an oven at a temperature of 110° C. for 1 hour, after which it is removed from the oven and allowed to stand for at least 18 hours. The peroxide is used to assist in the dispersion rather than to remove the organic matter. After the soil has been treated with peroxide as described above it is washed into the special dispersion cup and dispersed in the same manner as in method *A*, except that the time of dispersion is increased to 15 minutes.

It is important in all cases to see that the paddle on the dispersion machine is replaced as soon as it shows signs of wear.

After dispersion the mixture is transferred to the glass graduate, and distilled water having the same temperature as the constant temperature bath is added until the mixture attains a volume of 1,000 cubic centimeters. The graduate containing the soil suspension is then placed in the constant temperature bath. The suspension is stirred frequently with a glass rod to prevent settlement of particles in suspension. When the soil suspension attains the temperature of the bath the graduate is removed and its contents thoroughly shaken for one minute, the palm of the hand being used as a stopper over the mouth of the graduate. At the conclusion of this shaking the time is recorded, the graduate placed in the bath, and readings taken with the hydrometer at the end of both one and two minutes. The hydrometer is read at the top of the meniscus formed by the suspension around its stem to the nearest one-half gram per liter. Subsequent readings are taken at intervals of 5, 15, 30, 60, 250, and 1,440 minutes after the beginning of sedimentation. Readings on the thermometer placed in the constant temperature bath are made coincidentally with the hydrometer readings and recorded.

After each reading except the 1-minute reading, the hydrometer is very carefully removed from the soil suspension in such a manner as to cause no disturbance in the suspension, wiped clean, and laid aside. Fifteen or twenty seconds before the time for a reading it is again slowly and carefully placed in the soil suspension. This operation prevents soil particles from accumulating on the hydrometer and also prevents the hydrometer from reducing the horizontal sectional area of the suspension through which the soil particles settle. The reading is not taken until the hydrometer has come to rest.

6. *Sieve analysis.*—At the conclusion of the final reading the suspension is washed on a No. 200 sieve. That fraction retained on the No. 200 sieve is dried and then analyzed in a nest of sieves consisting of one each of the following: Nos. 20, 40, 60, and 140.

COMPUTATION OF DATA GIVEN BY MECHANICAL ANALYSIS

The data obtained from the three parts of the test, i. e. the separation of coarse material in the preparation of the sample, the hydrometer analysis, and the sieve analysis—are computed and combined as described below and illustrated in Tables 3 and 4.

1. *Hygroscopic moisture.*—The hygroscopic moisture is expressed as a percentage of the weight of the oven-dried soil and is one hundred times the quantity obtained by dividing the difference between the weight of the air-dried and the weight of the oven-dried soil by the weight of the oven-dried soil. The method of computation is illustrated in Table 3.

To correct the weight of the air-dried sample for hygroscopic moisture the given value is multiplied by the expression

$$\frac{100}{100+\text{per cent of hygroscopic moisture}}$$

This factor, as illustrated in Table 3, equals

$$\frac{100}{100+2.53}=0.975$$

Thus in Table 4 the weight of air-dried sample, 99.0 grams, multiplied by 0.975 equals 96.5 grams, the weight of dry soil dispersed.

2. *Coarse material.*—From the weight of the air-dried total test sample (318.3 grams, Table 3) the weight of the oven-dried fraction retained on the No. 10 sieve (56.2 grams, Table 3) is subtracted. The difference (262.1 grams, Table 3) is assumed to equal the weight of the air-dried fraction passing the No. 10 sieve. According to this assumption, no hygroscopic moisture is contained in the air-dried particles retained on the No. 10 sieve, when as a matter of fact a small

Table 3.—*Hygroscopic moisture and coarse material determinations for sample 4,422X*

HYGROSCOPIC MOISTURE	
Weight of air-dried soil, grams	15. 00
Weight of dish and air-dried soil, grams	41. 37
Weight of dish and oven-dried soil, grams	41. 00
Loss in weight, grams	0. 37
Weight of oven-dried soil, grams	14. 63
Hygroscopic moisture, percentage of weight of oven-dried soil	2. 53
Hygroscopic moisture correction factor	0. 975
COARSE MATERIAL	
Weight of total test sample, air-dried, grams	318. 3
Weight of washed and oven-dried fraction retained on No. 10 sieve, grams	56. 2
Weight of fraction passing No. 10 sieve, air-dried, grams	262. 1
Weight of fraction passing No. 10 sieve corrected for hygroscopic moisture, grams	255. 5
Weight of total test sample corrected for hygroscopic moisture, grams	311. 7
Weight of fraction retained on No. 4 sieve, oven-dried, grams	40. 6
Fraction retained on No. 4 sieve, percentage of corrected weight of total test sample	13. 0
Fraction retained on No. 10 sieve, percentage of corrected weight of total test sample	18. 0

percentage of moisture may be present in this fraction. This amount of moisture, compared with that held in the pores of the fraction passing the No. 10 sieve, is relatively small. Therefore any error produced by the assumption as stated is considered negligible in amount. The weight of the fraction passing the No. 10 sieve is corrected for hygroscopic moisture (255.5 grams, Table 3). To this value is added the weight of the oven-dried fraction retained on the No. 10 sieve to obtain the weight of the total test sample corrected for hygroscopic moisture (311.7 grams, Table 3). The fractions retained on both the No. 4 and the No. 10 sieve are expressed as percentages of the corrected weight of the total test sample (13.0 per cent and 18.0 per cent, respectively, Table 3).

3. *Percentage of soil in suspension.*—For temperatures of the constant temperature bath other than that at which the hydrometer was calibrated, the hydrometer readings are corrected in accordance with temperature correction factors such as are shown graphically as ΔR in Figure 3, A. A temperature correction curve of this type should be determined experimentally for each hydrometer in use. Thus in Table 4 the first hydrometer reading, 34, taken at 70° F. becomes 34.4 when corrected for temperature in accordance with Figure 3, A.

The percentage of the dispersed soil in suspension represented by different corrected hydrometer readings depends upon both the amount and the specific gravity of the soil dispersed.

If the specific gravity of the soil is 2.65, the hydrometer reading gives the weight of soil remaining in suspension in grams per liter of the mixture or suspension. The percentage of dispersed soil remaining in suspension is given by the expression

$$P=\frac{R}{W}\times 100$$

where P = percentage of originally dispersed soil remaining in suspension.

R = hydrometer reading.

W = weight of soil originally dispersed, in grams per liter of suspension.

If, as is the customary procedure, the volume of the suspension is 1 liter, the term W may be taken as the total weight of soil originally dispersed, without the qualifying phrase, "per liter of suspension."

If the specific gravity of the soil is other than 2.65, the percentage of originally dispersed soil remaining in suspension is given by the expression

$$P=\frac{Ra}{W}\times 100$$

in which a is a constant depending on the density of the suspension. The value of a, for a specific gravity G and a water density at 67° F. of 0.9984, is given by the equation

$$a=\frac{2.6500-0.9984}{2.6500}\times\frac{G}{G-0.9984}$$

Following are values of a for different values of the specific gravity:

Specific gravity, G	Constant, a
2.95	0.94
2.85	0.96
2.75	0.98
2.65	1.00
2.55	1.02
2.45	1.05
2.35	1.08

The percentage of the dispersed soil remaining in suspension may be obtained from this table by interpolation. It is sufficiently accurate, however, to select the constant for the specific gravity closest to that of the particular soil tested. Thus, in Table 4, sample No. 4,422X has a specific gravity of 2.41, and consequently the constant, 1.05, corresponding to a specific gravity of 2.45, is used.

A corrected hydrometer reading of 34.4 in Table 4, therefore, indicates a percentage of dispersed soil in suspension,

$$P=\frac{34.4\times 1.05}{96.5\times .01}=37.4 \text{ per cent}$$

For any hydrometer reading R the percentage of dispersed soil in suspension $=R\times 1.088$.

The percentage of the total test sample, including the fraction retained on the No. 10 sieve, is obtained by multiplying this result by the expression

$$\frac{100-\text{per cent retained on the No. 10 sieve}}{100}$$

Thus in Table 4, for a hydrometer reading of 34.4, the percentage of the total sample remaining in suspension is obtained by the computation

$$P_1=37.4\times\frac{100-18.1}{100}=30.7$$

This computation can be combined with the one above, allowing the percentage of the total sample remaining in suspension to be computed from the corrected hydrometer reading R. We have, therefore,

$$P_1=R\times 1.088\times 0.82=0.892\ R$$

Thus for a corrected hydrometer reading of 25.9, Table 4, we obtain the percentage of the total sample in suspension,

$$P_1=25.9\times 0.892=23.1$$

TABLE 4.—*Sieve and hydrometer analysis for sample No. 4,422X*

Percentage of sample retained on No. 10 sieve	18.0
Weight of air-dried sample, grams	99.0
Weight of dry soil dispersed, grams	96.5
Weight of total test sample represented by weight of dry soil, grams	117.7
Specific gravity	2.41
Plasticity index	8.0
Flocculation	None.

DETERMINATION OF PERCENTAGE OF SOIL IN SUSPENSION

Date tested	Time observed	Temperature	Hydrometer reading: Original	Hydrometer reading: Corrected for temperature (fig. 3, A).	Percentage of dispersed sample remaining in suspension, P	Percentage of total test sample remaining in suspension, P_1
		°F.				
July 29, 1929	9.41 a. m.					
Do	9.42 a. m.	70	34.0	34.4	37.4	30.7
Do	9.43 a. m.	70	25.5	25.9	28.2	23.1
Do	9.46 a. m.	70	19.0	19.4	21.1	17.3
Do	9.56 a. m.	70	15.0	15.4	16.8	13.7
Do	10.11 a. m.	70	12.0	12.4	13.5	11.1
Do	10.41 a. m.	70	10.5	10.9	11.9	9.7
Do	1.51 p. m.	70	7.0	7.4	8.1	6.6
July 30, 1929	9.41 a. m.	68	3.0	3.1	3.4	2.8

DETERMINATION OF SIZE OF SOIL PARTICLES IN SUSPENSION

Original hydrometer reading	Period of sedimentation, T	Grain diameter[1] D	Temperature	Correction coefficients: K_L, Fig. 3, B	K_G, Fig. 3, C	K_D, Fig. 3, D	Corrected grain diameter
	Minutes	Millimeters	°F.				Millimeters
34.0	1	0.078	70	0.48	1.08	0.98	0.0396
25.5	2	.055	70	.50	1.08	.98	.0291
19.0	5	.035	70	.51	1.08	.98	.0189
15.0	15	.020	70	.52	1.08	.98	.0110
12.0	30	.014	70	.53	1.08	.98	.0079
10.5	60	.010	70	.53	1.08	.98	.0056
7.0	250	.005	70	.54	1.08	.98	.0029
3.0	1,440	.002	68	.55	1.08	.99	.0012

[1] See table 5.

SIEVE ANALYSIS

Fraction	Weight	Percentage of total test sample
	Grams	
Passing No. 10, retained on No. 20	2.35	2.0
Passing No. 20, retained on No. 40	2.59	2.2
Passing No. 40, retained on No. 60	4.12	3.5
Passing No. 60, retained on No. 140	9.41	8.0
Passing No. 140, retained on No. 200	12.11	10.3

4. *Diameter of soil particles in suspension.*—The maximum diameters of the particles in suspension, based on Stokes's law for assumed conditions suggested in part by G. J. Bouyoucos, are shown in Table 5. (See Soil Science, vol. 26, No. 3, September, 1928, p. 234.)

According to Stokes's law,

$$d=\sqrt{\frac{30nL}{980\ (G-G_1)\ T}}$$

In this equation—

d = maximum grain diameter in millimeters.

n = coefficient of viscosity of the suspending medium (in this case water) in poises. Varies with changes in temperature of the suspending medium.

L = distance in centimeters through which soil particles settle in a given period of time.

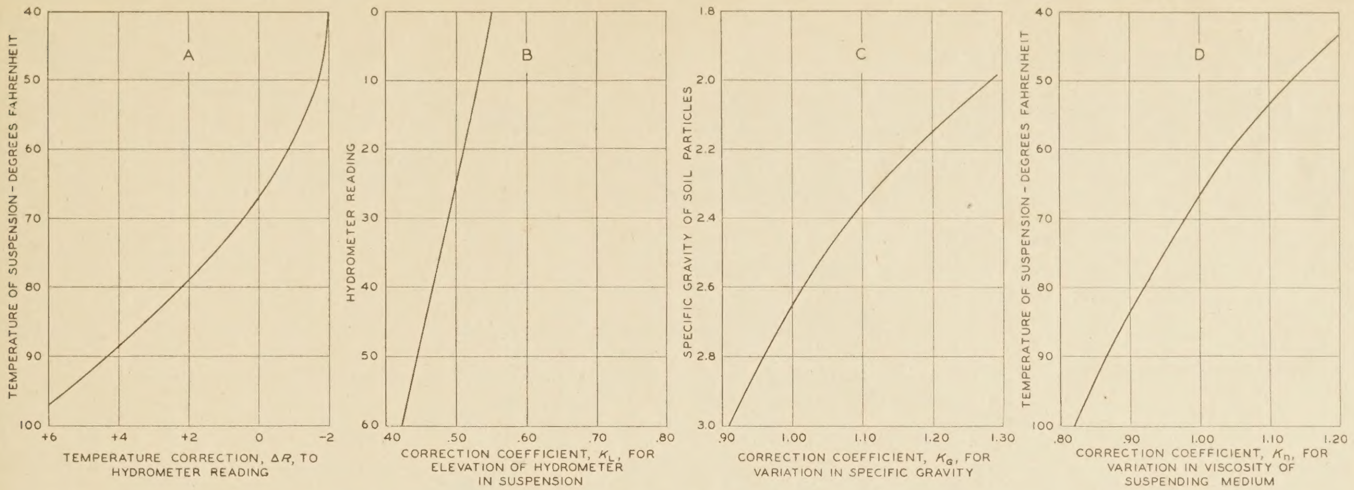

FIGURE 3.—CORRECTION CURVES FOR USE IN HYDROMETER ANALYSIS

T = time in minutes, period of sedimentation.
G = specific gravity of soil particles.
G_1 = specific gravity of the suspending medium. In this case $G_1 = 0.9984$, or approximately 1.0.

TABLE 5.—*Maximum grain diameters in suspension under assumed conditions*

Time	Maximum grain diameter in suspension
Minutes	*Millimeters*
1	0.078
2	.055
5	.035
15	.020
30	.014
60	.010
250	.005
1,440	.002

The grain diameters given in Table 5 are computed according to the following assumptions:

L, the distance through which the particle falls, is constant and equal to 32.5 centimeters.

n, the coefficient of viscosity, equals 0.0102, that of water at 67° F.[1]

G, the specific gravity of the soil particles, is constant and equal to 2.65.

As a matter of fact, the hydrometer reading is dependent, not on particles distributed throughout a depth of 32.5 centimeters in the suspension, but on those existing in that portion of the suspension holding the hydrometer.

In order to use Stokes's law to determine the diameter of the particles it is necessary to know the distance through which these particles fall in a given time. Since the density throughout a suspension is not uniform and varies with the grading of the material in suspension and the time of sedimentation, a fixed distance can not be used. For hydrometers of certain shapes the depth of the center of volume of the hydrometer below the surface of the suspension could be taken as the distance through which the particles may be assumed to fall. In the case of the Bouyoucos hydrometer it has been found by experiment that for the methods of dispersion described in this procedure an assumed distance which bears a constant ratio to the depth of the hydrometer in the suspension, but which is less than the distance indicated by the center of volume of the hydrometer, gives closer agreement to mechanical analysis performed by the pipette methods. The assumed distance of fall has been taken as 0.42 of the distance from the surface of the suspension to the elevation of the bottom of the hydrometer.

The specific gravities of the soil particles and the temperature of the suspension are likely to vary from those assumed in the preparation of Table 3. A better approximation to the true diameters of the soil particles is obtained by applying correction coefficients to the values given by Table 5.

Curves from which these coefficients may be derived are given in Figure 3. The correction coefficients for elevation of hydrometer (fig. 3, B) are obtained experimentally for each hydrometer in use. The coefficients for the specific gravity and the viscosity correction (figs. 3, C and 3, D, respectively) are independent of the apparatus used in the test.

Multiplication by the coefficient shown in Figure 3, B gives the maximum grain size at the reference elevation in the suspension instead of that at a depth of 32.5 centimeters. This coefficient varies with the hydrometer reading and is given by the expression,

$$K_L = \sqrt{\frac{\text{assumed depth of fall in centimeters}}{32.5}}$$

Multiplication by the coefficient shown in Figure 3, C corrects for variation in specific gravity[2] from that on which the sizes given in Table 5 are based and is given by the expression

$$K_G = \sqrt{\frac{1.65}{\text{specific gravity of soil particle} - 1}}$$

Multiplication by the coefficient shown in Figure 3, D corrects for the viscosity of water at temperatures other than 67° F., the temperature of the suspension assumed in the preparation of Table 5. The viscosity correction coefficient is given by the expression

$$K_n = \sqrt{\frac{\text{viscosity coefficient at given temperature}}{0.0102}}$$

The application of these coefficients is illustrated in Table 4. After a period of sedimentation of one minute

[1] Smithsonian Physical Tables, seventh revised edition, 1921, p. 155.

[2] The specific gravity of the soil should be obtained by the pycnometer method.

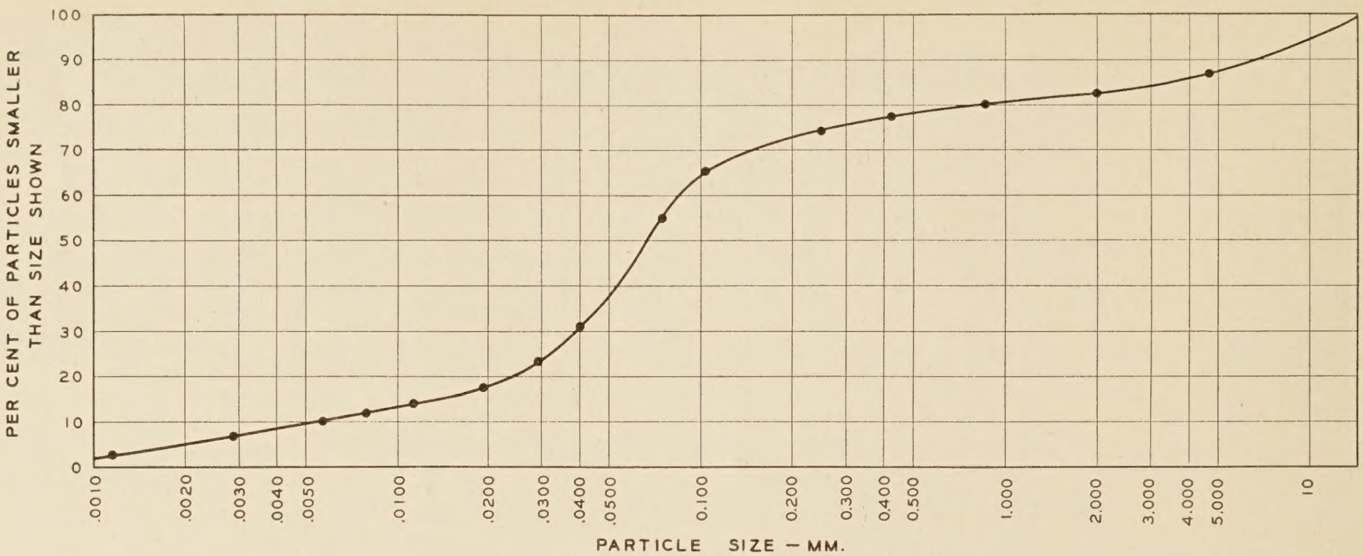

FIGURE 4.—GRAIN-SIZE ACCUMULATION CURVE FOR SOIL SAMPLE 4,422X

the grain diameter indicated by Table 5 is 0.078 millimeters. The uncorrected hydrometer reading was 34, the specific gravity was 2.41, and the temperature of the suspension was 70° F. The correction coefficients in this case are 0.48, corresponding to a hydrometer reading of 34 (fig. 3, B); 1.08, corresponding to a specific gravity of 2.41 (fig. 3, C); and 0.98, corresponding to a water temperature of 70° F. (fig. 3, D). The corrected grain diameter then becomes

$$0.078 \text{ millimeter} \times 0.48 \times 1.08 \times 0.98 = 0.040 \text{ millimeter}$$

5. *Sieve analysis.*—The percentage of the soil sample retained on each of the sieves in the sieve analysis is obtained by dividing the weight of fraction retained on each sieve by the weight of the oven-dried fraction dispersed (117.7 grams, Table 4) and multiplying by 100.

6. *Plotting.*—The percentages of grains of different diameters are plotted to a logarithmic scale to obtain "soil grain-diameter accumulation curves." Figure 4 shows a curve of this character representing the mechanical analysis of soil sample No. 4,422X.

7. *Record.*—The results are reported as follows:

Particles larger than 2 millimeters, per cent.
Coarse sand, 2.0 millimeters to 0.25 millimeter, per cent.
Fine sand, 0.25 millimeter to 0.05 millimeter, per cent.
Silt, 0.05 millimeter to 0.005 millimeter, per cent.
Clay, smaller than 0.005 millimeter, per cent.
Colloids, smaller than 0.001 millimeter, per cent.

DETERMINATION OF LIQUID LIMIT

1. *Definition.*—The liquid limit of a soil is that moisture content, expressed as a percentage of the weight of the oven-dried soil, at which the soil will just begin to flow when lightly jarred ten times.

2. *Apparatus.*—The apparatus consists of the following:

A porcelain evaporating dish about 4½ inches in diameter.
A flexible spatula having a blade about 3 inches long and about ¾ inch wide.
A grooving tool of dimensions shown in Figure 5.
Matched watch glasses which are held together by a suitable clamp and fit sufficiently tight to prevent loss of moisture during weighing.
An analytical balance sensitive to 0.001 gram.

3. *Sample.*—A sample weighing about 30 grams is taken from the thoroughly mixed portion of the material passing the No. 40 sieve.

4. *Procedure.*—The air-dried soil is placed in the evaporating dish and thoroughly mixed with water until the mass becomes pasty. The mass of soil is then shaped into a smooth layer about three-eighths inch thick at the center and divided into two portions with the grooving tool, as shown in Figure 6, top.

The dish is held firmly in one hand, with the groove parallel to the line of sight, and tapped lightly with a

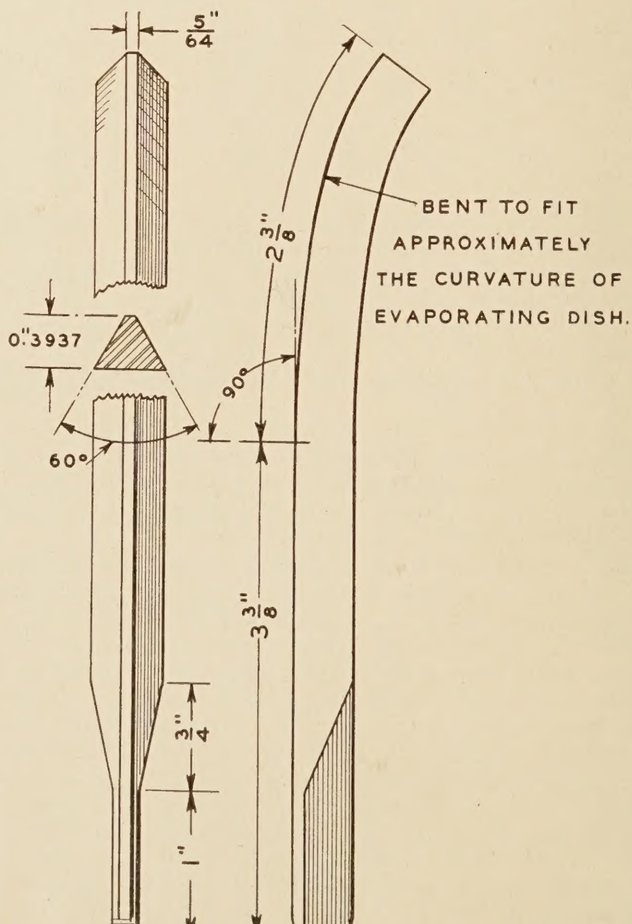

FIGURE 5.—GROOVING TOOL USED IN LIQUID LIMIT TEST

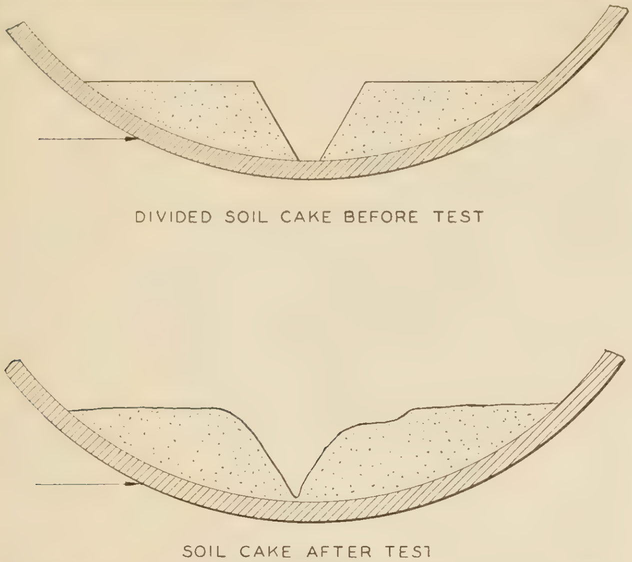

FIGURE 6.—DIAGRAM ILLUSTRATING LIQUID LIMIT TEST

horizontal motion against the palm of the other hand ten times. If the lower edges of the two soil portions do not flow together as shown in Figure 6, bottom, after ten blows have been struck, the moisture content is below the liquid limit. More water should be added and the procedure repeated. If the lower edges meet before ten blows have been struck, the moisture content is above the liquid limit, and dry soil should be added and the procedure repeated.

When the lower edges of the two portions of the soil cake just flow together as shown in Figure 6, bottom, after ten blows have been struck, the moisture content equals the liquid limit. To determine definitely whether the two portions are actually joined, the spatula is used to push one away from the other. If the two portions separate along the original line of division, the end point has not been reached, and the procedure is repeated with the addition of a small amount of water.

A small quantity of soil from that portion of the soil cake which has flowed is removed and placed in a pair of watch glasses. The watch glasses and soil are then weighed and the weight recorded as the weight of glass and wet soil (37.49 grams in Table 6). The soil in the glasses is oven-dried to constant weight at a temperature of 110° C. and weighed. This weight is recorded as the weight of glass and dry soil (28.15 grams, Table 6). The loss in weight due to drying (37.49 grams − 28.15 grams = 9.34 grams, Table 6) is recorded as the weight of water.

5. *Calculation.*—The liquid limit is expressed as the moisture content in percentage of the weight of the oven-dried soil. It is computed from the following formula:

$$L.\,L. = \frac{\text{weight of water}}{\text{weight of dry soil}} \times 100$$

Thus in Table 6 the liquid limit of sample S 5,214 is

$$\frac{9.34}{15.06} \times 100 = 62.0 \text{ per cent}$$

DETERMINATION OF PLASTIC LIMIT

1. *Definition.*—The plastic limit of a soil is the lowest moisture content, expressed as a percentage of the weight of the oven-dried soil, at which the soil can be rolled into threads one-eighth inch in diameter without the threads breaking into pieces.

TABLE 6.—*Plasticity determinations for sample S 5,214*

LIQUID LIMIT TEST	
Weight of glass and wet soil, grams	37.49
Weight of glass and dry soil, grams	28.15
Weight of glass, grams	13.09
Weight of water, grams	9.34
Weight of dry soil, grams	15.06
Liquid limit, per cent	62.0
PLASTIC LIMIT TEST	
Weight of glass and wet soil, grams	32.20
Weight of glass and dry soil, grams	28.59
Weight of glass, grams	12.17
Weight of water, grams	3.61
Weight of dry soil, grams	16.42
Plastic limit, per cent	22.0
Plasticity index, per cent	40.0

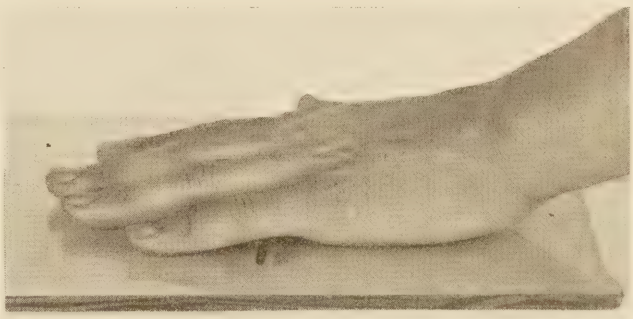

FIGURE 7.—ROLLING OF SOIL THREADS IN PLASTIC LIMIT TEST

2. *Apparatus.*—The apparatus consists of the following:

A porcelain evaporating dish about 4½ inches in diameter.
A flexible spatula having a blade about 3 inches long and about three-fourths inch wide.
A glass plate or piece of glazed paper on which to roll the sample.
Matched watch glasses which are held together by a suitable clamp and fit sufficiently tight to prevent loss of moisture during weighing.
An analytical balance sensitive to 0.001 gram.

3. *Sample.*—A sample weighing about 15 grams is taken from the thoroughly mixed portion of the material passing the No. 40 sieve.

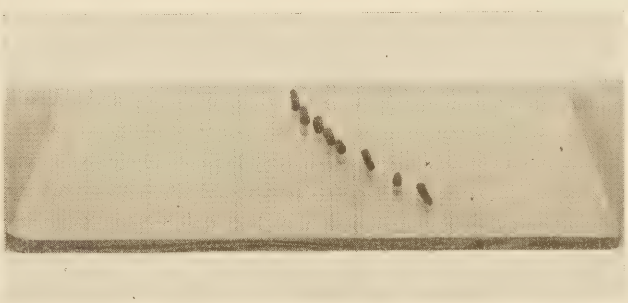

FIGURE 8.—CRUMBLED SOIL THREADS RESULTING FROM PLASTIC LIMIT TEST

4. *Procedure.*—The air-dried soil is placed in the evaporating dish and mixed with water until the mass becomes plastic enough to be easily shaped into a ball. The ball of soil is then rolled between the palm of the hand and the glass plate or piece of glazed paper with just sufficient pressure to form the soil mass into a thread. (Fig. 7.) When the diameter of the resulting thread becomes one-eighth of an inch the soil is kneaded together and again rolled out. This process is continued until the crumbling of the soil (as shown in fig. 8) prevents the formation of the thread. The portions of

the crumbled soil are then gathered together and placed in watch glasses. The watch glasses and soil are weighed and the weight recorded as the weight of glass and wet soil (32.20 grams, Table 6). The soil in the glasses is then oven-dried to constant weight at a temperature of 110° C. and weighed. This weight is recorded as the weight of glass and dry soil (28.59 grams, Table 6). The loss in weight (32.20 grams − 28.59 grams = 3.61 grams, Table 6) is recorded as the weight of water.

5. *Calculations.*—The plastic limit is expressed as the moisture content in percentage of the weight of the oven-dry soil. It is computed from the following formula:

$$P.\ L. = \frac{\text{weight of water}}{\text{weight of dry soil}} \times 100$$

Thus in Table 6 the plastic limit of sample S 5,214 equals

$$\frac{3.61}{16.42} \times 100 = 22.0 \text{ per cent}$$

DETERMINATION OF PLASTICITY INDEX

1. *Definition.*—The plasticity index of a soil is the difference between its liquid limit and its plastic limit.

2. *Calculation.*—The plasticity index is calculated by the formula $P.\ I. = L.\ L. - P.\ L.$

Thus in Table 6 the plasticity index of sample S 5,214 equals 62.0 − 22.0 = 40.0 per cent.

DETERMINATION OF CENTRIFUGE MOISTURE EQUIVALENT

1. *Definition.*—The centrifuge moisture equivalent of a soil is the amount of moisture, expressed as a percentage of the weight of the oven-dried soil, retained by a soil which has been first saturated with water and then subjected to a force equal to one thousand times the force of gravity for one hour.

2. *Apparatus.*—The apparatus consists of the following:

A porcelain Gooch crucible with perforated bottom. The crucible is about 1½ inches in height and about 1 inch in diameter at the top and three-fourths of an inch at the bottom, outside dimensions.

A circular piece of filter paper just large enough to cover the inside bottom of the Gooch crucible.

A Babcock trunnion cup fitted with a brass cap and with a rubber stopper with a hole in the center, as shown in Figure 9.

A centrifuge of such size and so driven that a force equal to one thousand times the force of gravity may be exerted on the center of gravity of the soil sample.

An analytical balance sensitive to 0.001 gram.

3. *Sample.*—A 5-gram sample is taken from the thoroughly mixed portion of the material passing the No. 40 sieve.

4. *Number of tests.*—Tests are made in duplicate. Table 7 shows the record for the two tests of sample S 5,214.

5. *Procedure.*—The sample is placed in the Gooch crucible, in which has previously been placed a piece of wet filter paper which just covers the bottom of the crucible. The crucible is placed in a pan of water and the sample allowed to take up moisture until completely saturated, as indicated by the presence of free water on the surface of the sample. It is then placed in a humidifier for at least 12 hours to insure uniform distribution of moisture throughout the soil mass. All free water then remaining on the surface of the sample is poured off, and the crucible is placed in a Babcock cup fitted with a rubber stopper, as shown in Figure

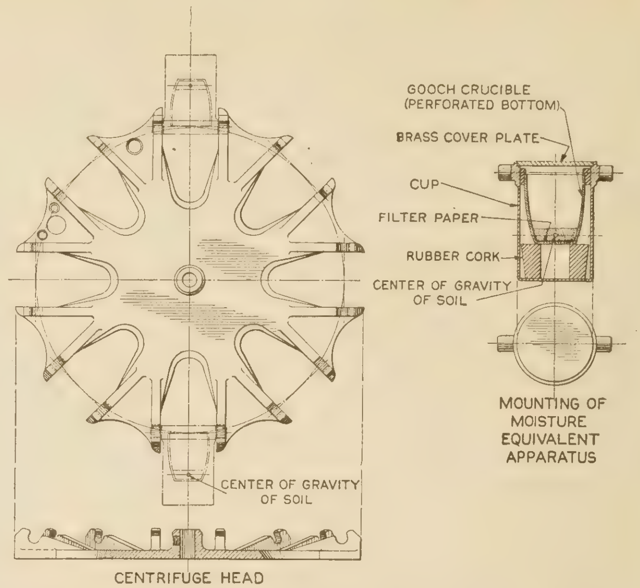

FIGURE 9.—APPARATUS FOR DETERMINING THE CENTRIFUGE MOISTURE EQUIVALENT

10. The hole in the stopper should be large enough to receive the water forced from the soil by the centrifuging operation. In addition to receiving the ejected water the stopper serves also as a cushion for the crucible. The sample is centrifuged for a period of one hour at a speed which, for the diameter of head used, will exert a centrifugal force one thousand times the force of gravity upon the center of gravity of the soil sample. Immediately after centrifuging, the crucible and contents are weighed and the weight recorded as the weight of crucible and contents after centrifuging (15.74 grams, Table 7). The sample is then oven-dried to constant weight at a temperature of 110° C. and weighed. This weight is recorded as the weight of crucible and contents after drying (12.82 grams, Table 7).

6. *Water-logging.*—When free water is observed on the top of the sample after the centrifuging operation the soil is said to have water-logged. This water is not removed, but is weighed with the sample.

7. *Calculation.*—The centrifuge moisture equivalent of the soil is calculated from the formula,

$$C.\ M.\ E. = \frac{(A-b)-(A_1-b_1)}{A_1-(c+b_1)} \times 100$$

in which

A = weight of crucible and contents after centrifuging.
A_1 = weight of crucible and contents after drying.
c = weight of crucible.
b = weight of filter paper wet.
b_1 = weight of filter paper dry.

Thus in Table 7 the centrifuge moisture equivalent of sample S 5,214, as given by the first test, is obtained by the computation,

$$C.\ M.\ E. = \frac{(15.74-0.20)-(12.82-0.10)}{12.82-(7.86+0.10)} \times 100 = \frac{2.82}{4.86} \times 100 = 58.0 \text{ per cent.}$$

8. *Variation.*—The variation between the two values obtained should not exceed 1 per cent for values of the moisture equivalent up to 15 and 2 per cent for values above 15.

TABLE 7.—*Determination of centrifuge moisture equivalent for sample S 5,214*

Test No.	Weight [1] of—			Centrifuge moisture equivalent
	Crucible and contents after centrifuging	Crucible and contents after drying	Crucible	
	Grams	*Grams*	*Grams*	*Per cent*
1	15.74	12.82	7.86	[2] 58.0
2	16.03	13.00	8.02	[2] 60.0
Average				59.0

[1] Weight of filter paper: Wet, b=0.20 gram; dry, b_1=0.10 gram.
[2] Water-logged.

DETERMINATION OF FIELD MOISTURE EQUIVALENT

1. *Definition.*—The field moisture equivalent of a soil is defined as the minimum moisture content, expressed as a percentage of the weight of the oven-dried soil, at which a drop of water placed on a smoothed surface of the soil will not immediately be absorbed by the soil but will spread out over the surface and give it a shiny appearance.

2. *Apparatus.*—The apparatus consists of the following:

A porcelain evaporating dish about 4½ inches in diameter.
A flexible spatula having a blade about 3 inches long and about three-fourths inch wide.
A pipette, burette, or similar device for adding water dropwise.
Matched watch glasses, held together by a suitable clamp and fitting sufficiently tight to prevent loss of moisture during weighing.
An analytical balance sensitive to 0.001 gram.

3. *Sample.*—A sample weighing about 50 grams is taken from the thoroughly mixed portion of the material passing the No. 40 sieve.

4. *Procedure.*—The air-dried sample is placed in the evaporating dish and mixed with water. Water is added in small amounts and the sample is thoroughly mixed after each addition of water. When the wetted soil forms into balls under manipulation the sample is smoothed off with a light stroke of the spatula and a drop of water is placed on the smoothed surface. If the water immediately disappears a few more drops of water are added, and the procedure is repeated until the water does not immediately disappear but spreads over the smoothed surface and leaves a shiny appearance. A small portion of the soil on which the last drop was placed is then removed and placed between two watch glasses. The weight of the watch glasses and wet soil is determined and recorded (32.08 grams, Table 8). The sample is then oven-dried to constant weight at a temperature of 110° C. and weighed. This weight is recorded as the weight of glass and dry soil (26.29 grams, Table 8). The difference in weight (32.08 grams − 26.29 grams = 5.79 grams, Table 8) is recorded as the weight of water.

5. *Calculations.*—The results obtained in the determination of the field moisture equivalent of sample S 5,214 are given in Table 8. The field moisture equivalent is computed by means of the formula

$$F.\ M.\ E. = \frac{\text{weight of water}}{\text{weight of oven-dried soil}} \times 100$$

Thus in Table 8 the field moisture equivalent of sample S 5,214 equals

$$\frac{5.79}{14.12} \times 100 = 41.0 \text{ per cent.}$$

76692—31——2

TABLE 8.—*Determination of field moisture equivalent of sample S 5,214*

Weight of glass and wet soil, grams	32.08
Weight of glass and dry soil, grams	26.29
Weight of glass, grams	12.17
Weight of water, grams	5.79
Weight of dry soil, grams	14.12
Field moisture equivalent, per cent	41.0

SHRINKAGE DETERMINATION

1. *Scope.*—This procedure furnishes the data from which the following subgrade soil constants may be computed: (*a*) Shrinkage limit, (*b*) shrinkage ratio, (*c*) volumetric change, (*d*) lineal shrinkage, and (*e*) specific gravity (approximate). Shrinkage determinations made on sample S 5,214 are recorded in Table 9.

2. *Apparatus.*—The apparatus consists of the following:

A porcelain evaporating dish about 4½ inches in diameter.
A flexible spatula having a blade about 3 inches long and about three-fourths inch wide.
A circular porcelain milk dish having a flat bottom and being about 1¾ inches in diameter by about one-half inch high.
A steel straightedge about 12 inches long.
A glass cup about 2 inches in diameter and about 1 inch high, the top rim of which is ground smooth and level.
A glass plate with three metal prongs for immersing the soil pat in mercury, as shown in Figure 10.
A glass graduate having a capacity of 25 cubic centimeters and graduated to 0.2 cubic centimeter.
An analytical balance sensitive to 0.001 gram.
Sufficient mercury to fill the glass cup to overflowing.

3. *Sample.*—A sample weighing about 30 grams is taken from the thoroughly mixed portion of the material passing the No. 40 sieve.

4. *Procedure.*—The sample is placed in the evaporating dish and thoroughly mixed with water in amount sufficient to fill the soil voids completely and to make the soil pasty enough to be readily worked into the porcelain milk dish without the inclusion of air bubbles. The amount of water required to furnish friable soils with the desired consistency is equal to or slightly greater than the liquid limit, and the amount necessary to furnish plastic soils with the desired consistency may exceed the liquid limit by as much as 10 per cent. The inside of the porcelain milk dish is coated with a thin layer of vaseline or some other heavy grease to prevent the adhesion of the soil to the dish.

An amount of the wetted soil equal to about one-third the volume of the milk dish is placed in the center of the dish, and the soil is caused to flow to the edges by tapping the dish on a firm surface cushioned by several layers of blotting paper or similar material. An amount of soil is added approximately equal to the first portion, and the dish is tapped until the soil is thoroughly compacted and all included air is brought to the surface. More soil is added and the tapping is continued until the dish is completely filled and excess soil stands out about its edge. The excess soil is then struck off with a straightedge, and all soil adhering to the outside of the dish is wiped off.

The dish when filled and struck off is weighed immediately and the weight recorded as the weight of dish and wet soil (29.34 grams, Table 9). The soil pat is allowed to dry in air until the color of the pat turns from dark to light. It is then oven-dried to constant weight at 110° C. and the weight recorded as the weight of dish and dry soil (22.61 grams, Table 9). The weight of the empty dish (11.52 grams, Table 9) is determined and recorded. The capacity of the dish in cubic centimeters, which is also the

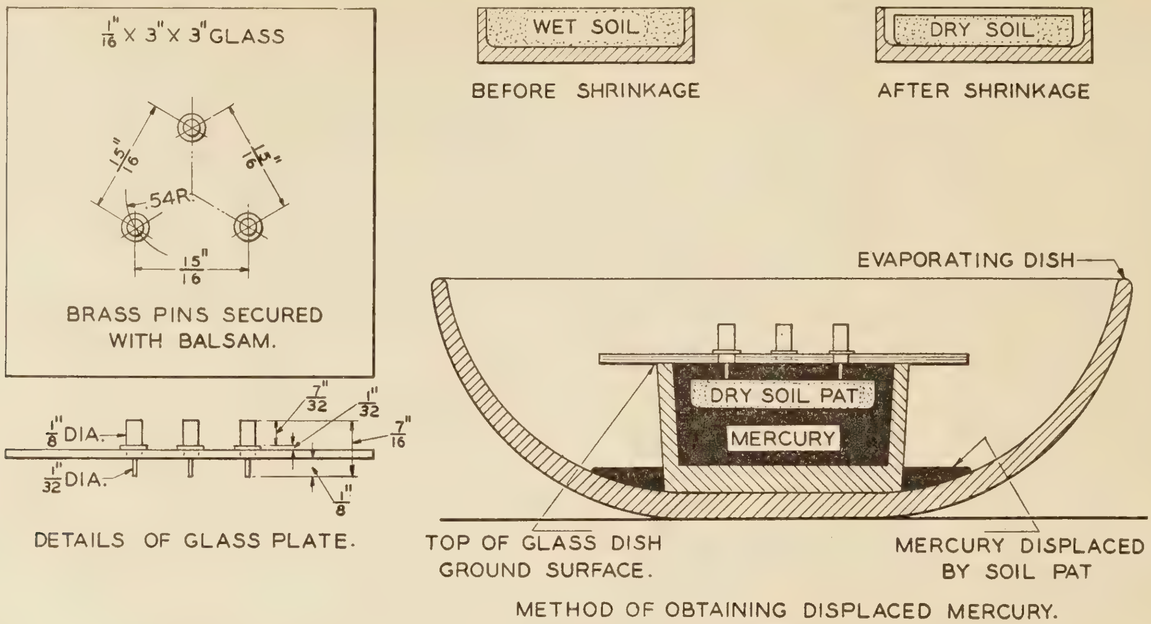

Figure 10.—Apparatus for Determining the Volumetric Change

volume of the wet soil pat, is determined by filling the dish to overflowing with mercury, removing the excess by pressing a glass plate firmly over the top of the dish, and measuring the volume of mercury held in the dish in the glass graduate. This volume is recorded as the volume of the wet soil pat, V (10.99 cubic centimeters, Table 9).

The volume of the dry soil pat is determined by removing the pat from the porcelain milk dish and immersing it in the glass cup full of mercury in the following manner: The glass cup is filled to overflowing with mercury and the excess mercury is removed by pressing the glass plate with the three prongs (fig. 10) firmly over the top of the cup. Any mercury which may be adhering to the outside of the cup is carefully wiped off. The cup, filled with mercury, is placed in the evaporating dish, and the soil pat is placed on the surface of the mercury. It is then carefully forced under the mercury by means of the glass plate with the three prongs (fig. 10) and the plate is pressed firmly over the top of the cup. It is essential that no air be trapped under the soil pat. The volume of the mercury so displaced is measured in the glass graduate and recorded as the volume of the dry soil pat, V_o (5.60 cubic centimeters, Table 9).

5. *Computations.*—The weight of the milk dish is subtracted from the weight of dish and wet pat to give the weight of the wet soil pat, W. The weight of the milk dish subtracted from the weight of dish and dry pat gives the weight of the dry soil pat, W_o The moisture content w of the soil at the time it was put in the dish, expressed as a percentage of the dry weight of the soil, is computed from the formula

$$w=\frac{W-W_o}{W_o}\times 100$$

Thus in Table 9

$$W=29.34-11.52=17.82 \text{ grams},$$

$$W^o=22.61-11.52=11.09 \text{ grams},$$

and

$$w=\frac{17.82-11.09}{11.09}\times 100=60.7 \text{ per cent.}$$

CALCULATION OF SHRINKAGE LIMIT

1. *Definition.*—The shrinkage limit of a soil is that moisture content, expressed as a percentage of the weight of the oven-dried soil, at which a reduction in moisture content will not cause a decrease in the volume of the soil mass, but at which an increase in moisture content will cause an increase in the volume of the soil mass.

2. *Computations.*—The shrinkage limit, S, is calculated from the data obtained in the volumetric shrinkage determination by the following formula:[3]

$$S=w-\left(\frac{V-V_o}{W_o}\times 100\right)$$

Thus in Table 9 the shrinkage limit of sample S 5,214 equals

$$60.7-\left(\frac{10.99-5.60}{11.09}\times 100\right)=12.1 \text{ per cent}$$

3. *Optional method.*—When both the true specific gravity, G, and the shrinkage ratio, R, are known, the shrinkage limit may be calculated from the formula:[3]

$$S=\left(\frac{1}{R}-\frac{1}{G}\right)\times 100$$

Thus in Table 9, if G and R were known first, the shrinkage limit of sample S 5,214 could be computed as follows:

$$S=\left(\frac{1}{1.98}-\frac{1}{2.60}\right)\times 100=12.1 \text{ per cent}$$

CALCULATION OF SHRINKAGE RATIO

1. *Definition.*—The shrinkage ratio of a soil is the ratio between a given volume change, expressed as a percentage of the dry volume, and the corresponding change in moisture content above the shrinkage limit, expressed as a percentage of the weight of the oven-dried soil. It equals the apparent specific gravity of the dried soil pat.

[3] See Public Roads, July, 1931, p. 125.

2. *Computations.*—The shrinkage ratio, R, is calculated from the data obtained in the volumetric shrinkage determination by the following formula:[3]

$$R=\frac{W_o}{V_o}$$

Thus in Table 9 the shrinkage ratio of sample S 5,214 equals

$$\frac{11.09}{5.60}=1.98$$

CALCULATION OF VOLUMETRIC CHANGE

1. *Definition.*—The volumetric change of a soil for a given moisture content is the volume change, expressed as a percentage of the dry volume, suffered by the soil mass when the moisture content is reduced from the stipulated percentage to the shrinkage limit. This stipulated moisture content is usually taken as the field moisture equivalent.

2. *Computation.*—The volumetric change, $V. C.$, is calculated from the data obtained in the volumetric shrinkage determination by the following formula:

$$V.\ C.=(w_1-S)R$$

where w_1 is the given moisture content.

If, as is customary, the volumetric change from the field moisture equivalent is desired, the formula assumes the form,

C_f = volumetric change from field moisture equivalent[4] $=(F.\ M.\ E.\ -S)R.$

Thus in Table 9 the volumetric change of sample S 5,214, when mixed with an amount of water equal to the field moisture equivalent (see Table 8) equals $(41.0-12.1)\times 1.98=57.2$ per cent.

CALCULATION OF LINEAL SHRINKAGE

1. *Definition.*—The lineal shrinkage of a soil for a given moisture content is the decrease in one dimension, expressed as a percentage of the original dimension, suffered by the soil mass when the moisture content is reduced from an amount equal to the field moisture equivalent to the shrinkage limit.

2. *Computation.*—The lineal shrinkage, $L. S.$, is obtained either by means of the formula[4]

$$L.\ S.=100\left(1-\sqrt[3]{\frac{100}{C_f+100}}\right)$$

or by means of the curve shown in Figure 11, which represents this relation. Thus in Table 9 the lineal shrinkage of sample S 5,214, as obtained from the formula, is 14.0 per cent.

TABLE 9.—*Volumetric shrinkage determination for sample S 5,214*

Weight of dish and wet soil, grams	29.34
Weight of dish and dry soil, grams	22.61
Weight of dish, grams	11.52
W, weight of wet soil pat, grams	17.82
W_o, weight of dry soil pat, grams	11.09
w, moisture content of wet soil pat, per cent	60.7
V, volume of dish, volume of wet soil pat, cubic centimeters	10.99
V_o, volume of dry soil pat, cubic centimeters	5.60
S, shrinkage limit, per cent	12.1
R, shrinkage ratio	1.98
C_f, volumetric change from field moisture equivalent, per cent	57.2
$L. S.$, lineal shrinkage, per cent	14.0
G, specific gravity (approximate)	2.60

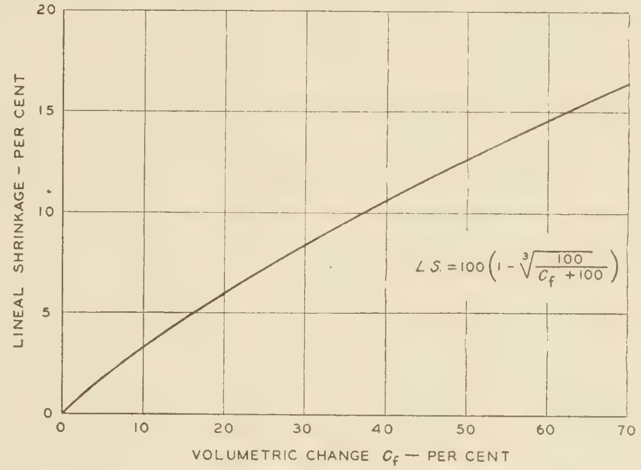

FIGURE 11.—RELATION BETWEEN VOLUMETRIC CHANGE AND LINEAL SHRINKAGE

APPROXIMATE CALCULATION OF SPECIFIC GRAVITY

1. *Definition.*—The specific gravity of a soil is the weight of the oven-dried soil divided by the true volume of the soil particles.

2. *Computations.*—The specific gravity, G, is calculated from the data obtained in the volumetric shrinkage test by the following formula:[4]

$$G=\frac{1}{\frac{1}{R}-\frac{S}{100}}$$

Thus in Table 9 the approximate specific gravity of sample S 5,214 is obtained by the computation

$$G=\frac{1}{\frac{1}{1.98}-\frac{12.1}{100}}=\frac{1}{0.384}=2.60$$

[3] See PUBLIC ROADS, July, 1931, p. 125.

[4] See PUBLIC ROADS, July, 1931, pp. 130 and 131.

GRAPHICAL SOLUTION OF THE DATA FURNISHED BY THE HYDROMETER METHOD OF ANALYSIS

Reported by E. A. WILLIS, Assistant Highway Engineer, F. A. ROBESON, Junior Highway Engineer, and C. M. JOHNSTON, Junior Civil Engineer, United States Bureau of Public Roads

THE HYDROMETER method of mechanical analysis described previously in this issue of Public Roads includes the following two separate operations: (*a*) The determination of the percentage of dispersed soil particles remaining in suspension at a given time, as indicated by particular hydrometer readings, and (*b*) the determination of the maximum size of soil particles in suspension corresponding to the percentages represented by particular hydrometer readings. The percentage of particles in suspension is determined by the hydrometer reading corrected for the conditions under which the test is performed. The maximum grain size at the time of any particular hydrometer reading is computed by means of Stokes's law. The method of obtaining the data is described in the preceding article (pp. 197 to 207 of this issue), Procedures for Testing Soils for the Determination of the Subgrade Soil Constants.

PERCENTAGE DETERMINATION

The Bouyoucos hydrometer, like any other, depends upon the density of the suspending medium for its buoyancy. It is calibrated in grams of soil per liter of suspension for assumed conditions of temperature of suspension and specific gravity of soil grains. Consequently, the actual number of grams per liter for any particular case is given directly by the hydrometer reading only if the conditions are identical with those for which the hydrometer was calibrated. For any other conditions suitable corrections must be made. For example, the hydrometer referred to in this discussion has been calibrated for a suspension temperature of 67° F. and a specific gravity of soil particles of 2.65. For temperatures other than 67° F. and specific gravities other than 2.65, the weight of soil remaining in suspension, in grams per liter of suspension, can be obtained by adding a temperature correction to the hydrometer reading and multiplying the sum by a specific gravity correction. The weight thus obtained is expressed as a percentage of the weight of soil originally dispersed. Both weights are given in grams of soil per liter of suspension, but, since the volume of the suspension is ordinarily one liter, the qualifying phrase, "per liter of suspension," is omitted for convenience in the discussion which follows.

When the temperature of the suspension, the specific gravity of the soil particles, and the weight of soil originally dispersed are known, the percentage of soil remaining in suspension for a given hydrometer reading may be determined graphically by the use of a chart laid out on cross-section paper, as illustrated in Figure 1. On this chart ordinates denote hydrometer readings and abscissas denote percentages of soil in suspension. Since the hydrometer is calibrated to give a correct reading in grams per liter when the temperature is 67° F. and the specific gravity is 2.65, these values are used as the base, or standard, to which the graphical corrections are referred. The value 50 grams was chosen as the basic value for the weight of soil originally dispersed. The relation between hydrometer reading and percentage of soil in suspension established by these three standard values is shown as a broken line in Figure 1.

The equation relating the hydrometer reading to the percentage of soil in suspension may be expressed as follows:

Let

R = hydrometer reading.

W = weight of soil originally dispersed per liter of suspension.

w = weight of soil in suspension per liter of suspension.

ΔR = correction to hydrometer reading for variation in temperature from 67° F.

a = correction coefficient for variation in specific gravity from 2.65.

$= \frac{2.6500-0.9984}{2.6500} \times \frac{G}{G-0.9984}$, where G is the specific gravity of the soil.[1]

P = percentage of originally dispersed soil remaining in suspension.

For the standard values of temperature and specific gravity (67° F. and 2.65),

$$w = R$$

For other values,

$$w = (R+\Delta R)a$$

The percentage of soil in suspension is given by the equation

$$P = \frac{(R+\Delta R)a}{W} \times 100 \text{ - - - - - - - - - - - - - (1)}$$

This equation may be written

$$P = (R+\Delta R) \times \frac{a}{W} \times 100 \text{ - - - - - - - - - - - - - (1)}$$

For the basic or standard conditions we have

$$\Delta R = 0,\ a = 1,\ W = 50,$$

so that the basic relation is given by the equation

$$P = \frac{R}{50} \times 100 = 2R$$

The manner in which the chart is constructed and the method of applying the various corrections are explained in the following paragraphs.

Temperature correction.—In Table 1 are given the values of the correction, ΔR, for variations in temperature from 67° F., obtained experimentally for the hydrometer used as an example in this discussion. If in equation (1) we put $P = 0$ we have

$$R = -\Delta R$$

It follows, therefore, that if the line represented by equation (1) should be plotted on the chart (fig. 1) its intercept on the axis of ordinates would be the point 0, $-\Delta R$. In the lower left-hand corner of Figure 1 values of ΔR taken from Table 1 are laid off as ordinates corresponding to values of the temperature from 60° to 90° F. A zero ordinate corresponds to a temperature of 67° F. and positive values of ΔR are plotted downward. By means of this scale the intercept, $-\Delta R$, for any given temperature of suspension, is readily obtained.

It will be noted in equation (1) that the slope of the line is given by the expression $\frac{a}{W} \times 100$. It is evident

[1] See preceding article, Procedures for Testing Soils for the Determination of the Subgrade Soil Constants, p. 200 of this issue.

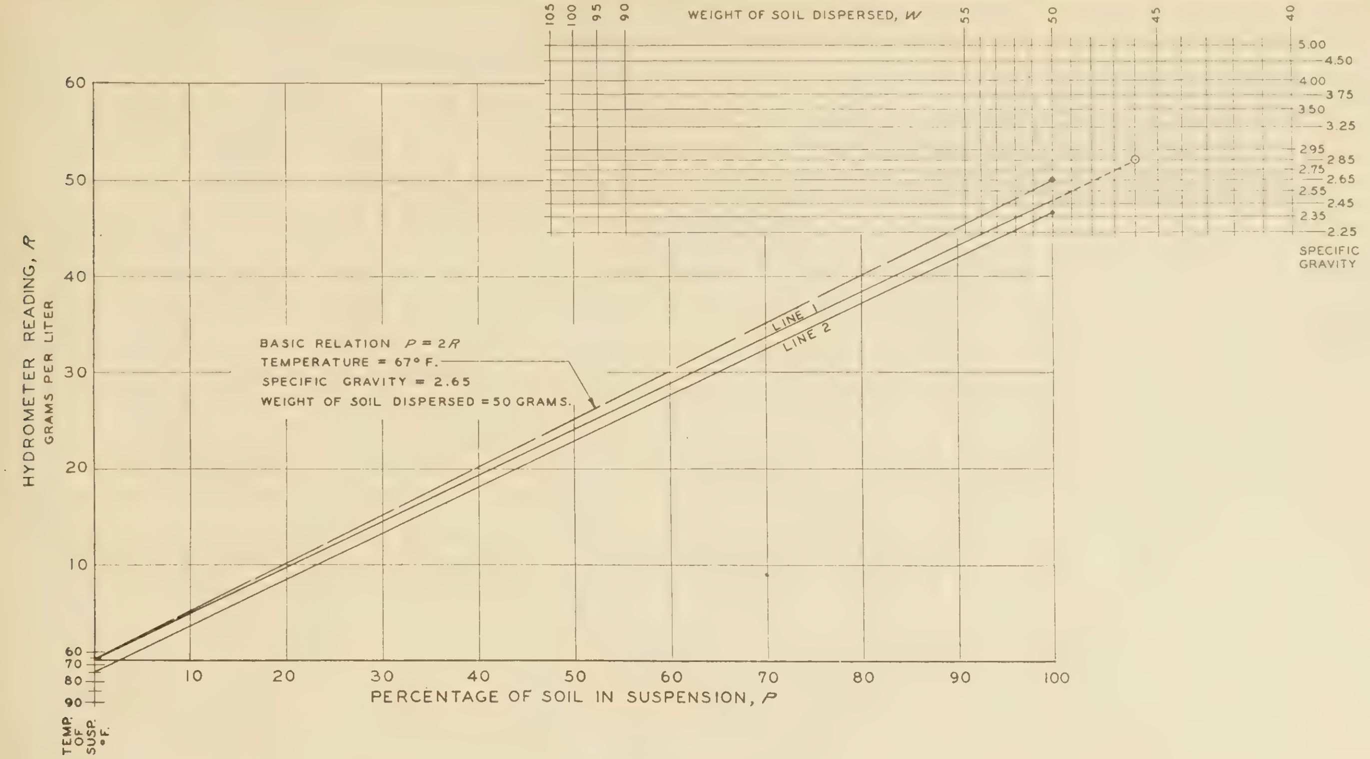

FIGURE 1.—CHART FOR CONVERTING HYDROMETER READINGS TO PERCENTAGES OF ORIGINALLY DISPERSED SOIL REMAINING IN SUSPENSION

TABLE 1.—*Temperature corrections to be added to the hydrometer readings*

Suspension temperature	Correction, ΔR
Degrees F.	*Grams per liter*
60	−0.8
65	−0.3
67	0.0
70	+0.4
75	+1.2
80	+2.2
85	+3.2
90	+4.3

that variations in the relation between P and R caused by variations in the specific gravity and the weight of soil dispersed are cared for by changes in the slope of the line.

Correction for specific gravity.—Assuming the basic values, $\Delta R=0$, $W=50$, we have, from equation (1)

$$P=\frac{Ra}{50}\times 100=2Ra$$

Setting $P=100$, we have

$$R=\frac{50}{a} \qquad (2)$$

Equation (2) gives the value of the hydrometer reading at 100 per cent suspension for any given value of specific gravity as indicated by the value of a. In Table 2 are given values of the quantity $\frac{50}{a}$ and also of the quantity $\frac{50}{a}-50$, the correction which must be added to or subtracted from the basic value 50 to obtain the correct reading for 100 per cent suspension.

In the upper right-hand corner of Figure 1, values of the quantity $R=\frac{50}{a}$ are laid off as ordinates correspond-

TABLE 2.—*Values of specific gravity constant, a, $\frac{50}{a}$, and $\frac{50}{a}-50$ for different values of the specific gravity*

Specific gravity of soil particles, G	Specific gravity constant, a	$\frac{50}{a}$	Hydrometer correction for reading of 50
		Grams per liter	*Grams per liter*
2.25	1.1204	44.6	−5.4
2.35	1.0836	46.1	−3.9
2.45	1.0519	47.5	−2.5
2.55	1.0243	48.8	−1.2
2.65	1.0000	50.0	0.0
2.75	0.9785	51.1	+1.1
2.85	0.9593	52.1	+2.1
2.95	0.9421	53.1	+3.1
3.25	0.8996	55.6	+5.6
3.50	0.8720	57.3	+7.3
3.75	0.8494	58.9	+8.9
4.00	0.8306	60.2	+10.2
4.50	0.8009	62.4	+12.4
5.00	0.7787	64.2	+14.2

ing to values of the specific gravity from 2.25 to 5.00. Thus, for a specific gravity of 2.65 the ordinate is 50; for a value of 5.00 the ordinate is 64.2, etc. When the weight of soil dispersed is 50 grams the slope of the line represented by equation (1) is obtained by drawing a line through the origin intersecting the abscissa $P=100$ at the value of R corresponding to the given specific gravity.

Correction for weight of soil dispersed.—Assuming the basic values, temperature = 67° F. and specific gravity of soil = 2.65; i. e., $\Delta R=0$, $a=1$, we have, in equation (1)

$$P=\frac{R}{W}\times 100$$

Setting $R=50$, we have

$$P=\frac{5{,}000}{W} \qquad (3)$$

Equation (3) gives the percentage of soil in suspension for a hydrometer reading of 50 and a weight of dispersed soil, W. Values of the quantity $\frac{5,000}{W}$ are given in Table 3 for values of W between 40 and 55 grams and between 90 and 105 grams. The lower interval is for use in the hydrometer analysis of silt and clay soils, the higher interval for use in the case of sandy soils. Values of the quantity $\frac{5,000}{W}$ are plotted as abscissas, in the upper right-hand portion of Figure 1, for indicated values of the weight of soil dispersed, W. Thus, as in Table 3, 50 grams of soil dispersed corresponds with 100 per cent of soil in suspension, 100 grams corresponds with 50 per cent, etc. When the specific gravity of the soil is 2.65, the slope of the line represented by equation (1) is obtained by drawing a line through the origin intersecting the ordinate $R=50$ at the value of P corresponding to the given value of W.

TABLE 3.—*Values of the quantity* $\frac{5,000}{W}$, *giving the percentage of particles in suspension indicated by a hydrometer reading of 50 for different weights of dry soil originally dispersed. (Specific gravity=2.65; temperature of suspension=67° F.)*

Weight of dry soil dispersed, W, per liter of suspension	Percentage in suspension, P, for hydrometer reading of 50	Weight of dry soil dispersed, W, per liter of suspension	Percentage in suspension, P, for hydrometer reading of 50
Grams		*Grams*	
40.0	125.0	90.0	55.6
41.0	122.0	91.0	54.9
42.0	119.1	92.0	54.3
43.0	116.3	93.0	53.8
44.0	113.7	94.0	53.2
45.0	111.1	95.0	52.6
46.0	108.7	96.0	52.1
47.0	106.4	97.0	51.5
48.0	104.2	98.0	51.0
49.0	102.0	99.0	50.5
50.0	100.0	100.0	50.0
51.0	98.0	101.0	49.5
52.0	96.2	102.0	49.0
53.0	94.3	103.0	48.5
54.0	92.6	104 0	48.1
55.0	90.9	105.0	47.6

For given values of temperature of suspension, specific gravity of soil, and weight of soil originally dispersed per liter of suspension, the line represented by equation (1), giving the relation between hydrometer reading and percentage of soil in suspension, is laid out on the chart of Figure 1 by the following process:

1. A straightedge is placed on the chart so as to intersect the origin and a point whose abscissa corresponds with the given weight of soil dispersed and whose ordinate corresponds with the given specific gravity, as indicated by the scales shown in the upper right-hand corner of Figure 1.

2. The straightedge is then moved parallel to its original position until it intersects the axis of ordinates at a point corresponding to the given temperature of suspension, as indicated by the temperature scale in the lower left-hand corner of Figure 1. A line is then drawn which represents the required relation between P and R.

To illustrate this operation, let us assume that 46.0 grams of soil having a specific gravity of 2.85 were dispersed and that the temperature of the suspension remained constant at 75° F. Line 1 in Figure 1, intersecting the origin and a point whose coordinates correspond with 46.0 grams of soil dispersed and a specific gravity of 2.85, represents the first position of the straightedge. Line 2, which intersects the axis of ordinates at a point corresponding to 75° F., gives the desired relation between P and R.

Values given by line 2 may be checked by computations based on equation (1). From Tables 1 and 2 we obtain the values, $\Delta R=+1.2$ and $a=0.9593$.

Substituting in equation (1), we have

$$P=(R+1.2)\,\frac{0.9593}{46.0}\times 100$$

$$=(R+1.2)\ 2.086$$

If $P=0$, $R=-1.2$. If $R=32.0$, $P=69.3$ These values will be found to check with those given by line 2.

DETERMINATION OF GRAIN SIZE

The second distinct operation in the graphical solution of the data furnished by the hydrometer analysis consists of determining the maximum grain size in suspension at any given time from Stokes's law, which is expressed by the formula

$$d=\sqrt{\frac{30nL}{980\,(G-G_1)\,T}}\text{------------}(4)$$

Where

d = maximum grain diameter in millimeters.
n = coefficient of viscosity of the suspending medium, in poises.
L = distance in centimeters through which soil particles settle.
T = time in minutes, period of sedimentation.
G = specific gravity of soil particles.
G_1 = specific gravity of the suspending medium.

In order that Stokes's law may serve to disclose the diameter of the soil particles it is necessary to know the distance through which these particles fall in a given time. As has been explained previously in the report, Procedures for Testing Soils for the Determination of the Subgrade Soil Constants, the distance, L, through which the soil particles are assumed to settle, in the determination of the grain size by means of the Bouyoucos hydrometer, equals 0.42 of the total distance between the surface of the suspension and the elevation of the bottom of the hydrometer.

When the hydrometer reading, the temperature of the suspension, the period of sedimentation, and the specific gravity of the soil particles are known, the particle diameter may be determined graphically by the use of a chart constructed as shown in Figure 2. The chart is plotted on semilogarithmic cross-section paper, on which the ordinates denote hydrometer reading and the abscissas denote period of sedimentation.

In the preceding article (p. 201 of this issue) variations in L, n, and G (equation 4) were cared for by means of correction coefficients applied to values of d computed on the basis of the standard conditions, temperature = 67° F., $G=2.65$, and $L=32.5$ centimeters. The graphical method here described does not involve the use of the standard value, $L=32.5$ centimeters. Values of L as determined by actual measurements of the hydrometer in use are substituted in the equation, and recourse to a correction factor is eliminated. The manner in which variations of L, n, and G are cared for is described in the following paragraphs.

Variations in the factor L.—Solving equation (4) (Stokes's law) for T, the period of sedimentation, we have

$$T=\frac{30nL}{980\,(G-G_1)\,d^2}\text{------------}(5)$$

Values of T as a function of L, the distance through which the soil settles, and d, the maximum diameter of

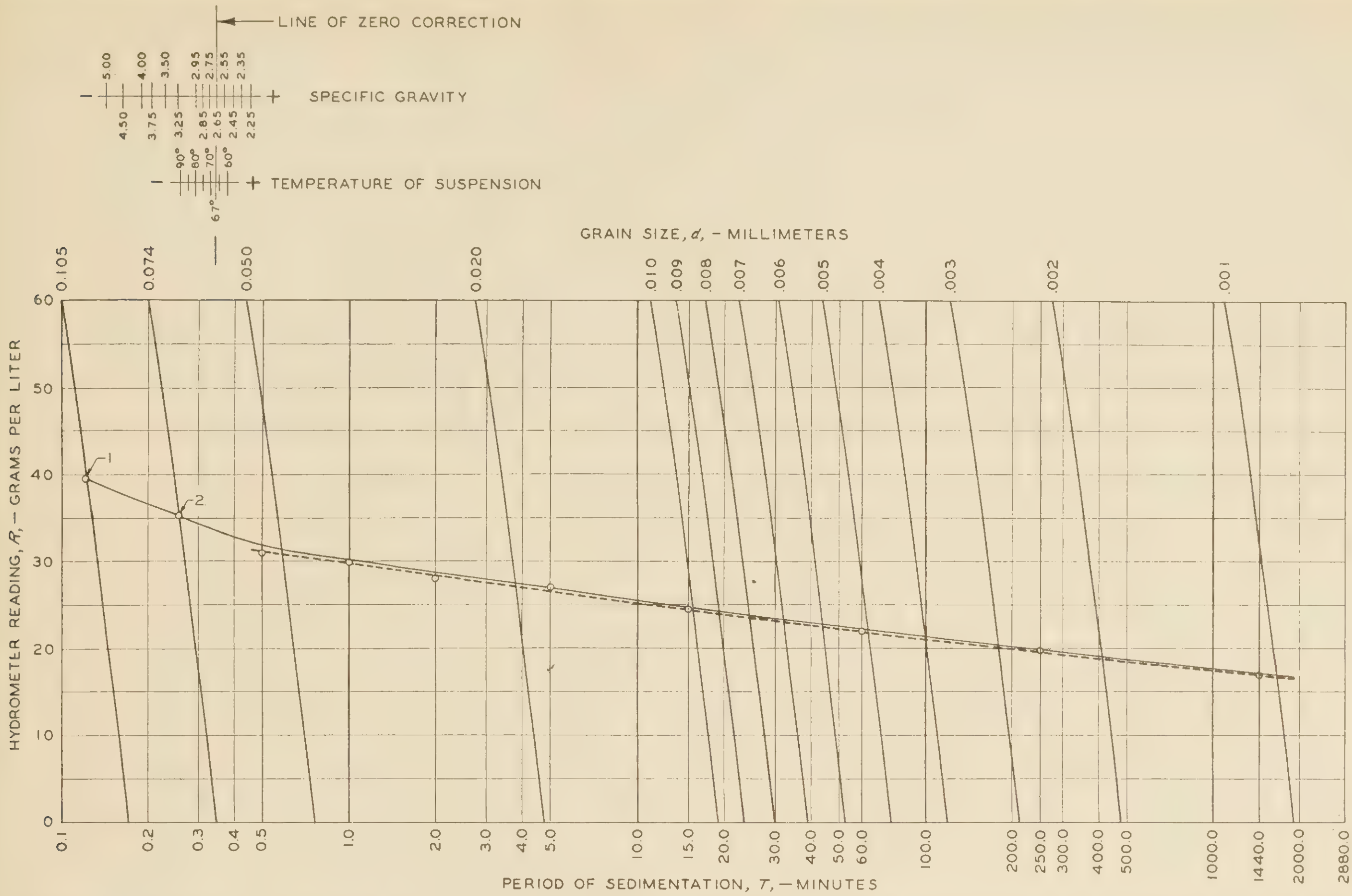

FIGURE 2.—CHART FOR OBTAINING FROM TEST DATA THE HYDROMETER READINGS CORRESPONDING TO SPECIFIC GRAIN SIZES

TABLE 4.—*Time of sedimentation as a function of grain diameter, d, and hydrometer reading, R. (Specific gravity=2.65; temperature of suspension=67° F.)*

Hydrometer reading, R	L	Time, T, in minutes for the following diameters—													
		0.105 millimeters	0.074 millimeters	0.050 millimeters	0.020 millimeters	0.010 millimeters	0.009 millimeters	0.008 millimeters	0.007 millimeters	0.006 millimeters	0.005 millimeters	0.004 millimeters	0.003 millimeters	0.002 millimeters	0.001 millimeters
Grams per liter	*Centimeters*														
0	10.00	0.171	0.345	0.756	4.73	18.9	23.3	29.5	38.6	52.5	75.6	118.0	210	473	1,891
10	9.25	.159	.319	.700	4.37	17.5	21.6	27.3	35.7	48.6	70.0	109.0	194	437	1,749
20	8.47	.145	.292	.641	4.00	16.0	19.8	25.0	32.7	44.5	64.1	100.0	178	400	1,601
30	7.78	.133	.269	.588	3.68	14.7	18.2	23.0	30.0	40.9	58.8	91.9	163	368	1,471
40	7.07	.121	.244	.535	3.34	13.4	16.5	20.9	27.3	37.1	53.5	83.5	149	334	1,337
50	6.37	.109	.220	.482	3.01	12.0	14.9	18.8	24.6	33.5	48.2	75.3	134	301	1,204
60	5.75	.099	.199	.435	2.72	10.9	13.4	17.0	22.2	30.2	43.5	67.9	121	272	1,087

soil particle remaining in suspension, are given in Table 4. The values of L to be used were determined by measurement for hydrometer readings from 0 to 60. The following quantities were assumed to be constant:

$n=0.0102$, the coefficient of viscosity of water at 67° F.
$G=2.65$.
$G_1=0.9984$, the density of water at 67° F.

The significance of Table 4 may be made clear by consideration of specific values. Thus, if the hydrometer reading, after a sedimentation period of 0.269 minutes, has the value 30, the maximum diameter of soil particles remaining in suspension is 0.074 millimeters. If, on the other hand, it takes 30 minutes for the hydrometer reading to reach the value 30, the maximum diameter of soil particles is 0.007 millimeters.

The values given in Table 4 are plotted in Figure 2 as curves showing the relation between hydrometer reading and period of sedimentation for different values of d, the maximum grain size. The relation between hydrometer reading and maximum grain size for a hydrometer analysis in which the temperature of suspension was 67° F. and the specific gravity of the soil was 2.65 may be obtained by plotting hydrometer readings against periods of sedimentation, as given by the analysis, on the chart of Figure 2. Intersections of the curve so determined with the grain-diameter curves give the hydrometer readings corresponding to specific values of maximum diameter of soil in suspension.

Variations in temperature and specific gravity.—Equation (5) may be written

$$T=\frac{30L}{980d^2}\times n\times\frac{1}{G-G_1} \qquad (5)$$

For a temperature of 67° F. and a specific gravity of 2.65, we have

$$T_o = \frac{30L}{980d^2} \times 0.0102 \times \frac{1}{2.6500 - 0.9984}$$

so that

$$\frac{T}{T_o} = \frac{n}{0.0102} \times \frac{1.6516}{G - G_1}$$

Let

$$C_n = \frac{n}{0.0102}$$

and

$$C_G = \frac{1.6516}{G - G_1}$$

$$= \frac{1.65}{G - 1} \text{ (approximately).}$$

Then

$$T = T_o \times C_n \times C_G,$$

and

$$\text{Log } T = \text{Log } T_o + \log C_n + \log C_G \text{ ------- (6)}$$

The grain-diameter curves plotted in Figure 2 give correct values of T, the period of sedimentation, for the standard conditions, temperature = 67° F. and $G = 2.65$. To obtain correct values for other temperatures and specific gravities, it is necessary to multiply all values of T by the factor $C_n \times C_G$. Since the scale of T is logarithmic, it is evident that the correction can be applied by displacing the entire system of curves horizontally a distance equal to the algebraic sum of the corrections, $\log C_n + \log C_G$. If this sum is positive, the curves should be shifted to the right; if negative, to the left.

Values of the viscosity coefficient of water, n, the temperature correction $C_n = \frac{n}{0.0102}$, and $\log_{10} C_n$ are given in Table 5 for temperatures varying from 60° to 90° F. Values of C_n are plotted against temperature of suspension in the upper left-hand corner of Figure 2 to the same logarithmic scale as that to which the period of sedimentation is plotted on the main chart. The reference line (temperature = 67° F., $C_n = 1.00$, $\log C_n = 0$) may be taken at any convenient point. Distances along this correction scale may be laid off directly from the logarithmic scale by the use of dividers. For construction purposes the actual lengths may be computed accurately by multiplying each value of $\log C_n$ by the length of one cycle on the chosen logarithmic scale.

TABLE 5.—*Values of the viscosity coefficient,[1] n, of water at various temperatures, of the coefficient* $C_n = \frac{n}{0.0102}$*, and of* $\log_{10} C_n$.

Temperature	n	Coefficient C_n	$\log_{10} C_n$
° F.	Poises		
60	0.0112	1.10	0.04139
65	.0105	1.03	0.01284
67	.0102	1.00	0.00000
70	.00978	0.959	−0.01818
75	.00917	0.899	−0.04624
80	.00861	0.844	−0.07366
85	.00810	0.794	−0.10018
90	.00764	0.749	−0.12552

[1] Smithsonian Physical Tables, seventh revised edition, 1921.

Similarly, values of C_G and $\log_{10} C_G$ are given in Table 6 for specific gravities varying from 2.25 to 5.00, and a logarithmic scale of these corrections is shown above the temperature correction scale in Figure 2.

As stated above, the grain-diameter curves may be corrected for given values of temperature and specific gravity by horizontal displacement in the direction indicated by the sign of the correction. To plot a point representing a given hydrometer reading and a given period of sedimentation, it is necessary to apply the correction in the opposite direction, i. e., positive to the left. The relative position of the point with respect to the curves is then the same as if the curves had been shifted to the right (or to the left, in the case of a negative correction).

TABLE 6.—*Values of the specific gravity correction,* $C_G = \frac{1.65}{G-1}$*, and of* $\log_{10} C_G$*, for values of the specific gravity, G, from 2.25 to 5.00*

Specific gravity, G	Coefficient, C_G	$\log_{10} C_G$
2.25	1.320	0.1206
2.35	1.222	0.0872
2.45	1.138	0.0561
2.55	1.064	0.0272
2.65	1.000	0.0000
2.75	0.943	−0.0256
2.85	0.892	−0.0497
2.95	0.846	−0.0726
3.25	0.733	−0.1347
3.50	0.660	−0.1805
3.75	0.600	−0.2218
4.00	0.550	−0.2596
4.50	0.471	−0.3266
5.00	0.412	−0.3846

METHOD OF USING CHARTS DESCRIBED

In Table 7 are given the data obtained in the hydrometer analysis of a soil sample. The following paragraphs describe the steps involved in using the charts of Figures 1 and 2 to develop from this material the data on which the grain-size accumulation curve is based. The results thus obtained are given in Table 8.

TABLE 7.—*Sieve and hydrometer analysis of sample 5,394X*

A.—GENERAL DATA

Weight of air-dried sample, grams	49.0
Weight of dry soil dispersed, grams	46.0
Specific gravity	2.85
Plasticity index	18.0

B.—HYDROMETER TEST DATA[1]

Date tested	Time observed	Temperature	Hydrometer reading	Period of sedimentation
		°F.	Grams per liter	Minutes
June 25, 1930	9.30 a. m.			0
Do	9.30.5 a. m.	76	31.0	0.5
Do	9.31 a. m.	75	30.0	1
Do	9.32 a. m.	75	28.0	2
Do	9.35 a. m.	75	27.0	5
Do	9.45 a. m.	75	24.5	15
Do	10.00 a. m.	74	24.0	30
Do	10.30 a. m.	74	22.0	60
Do	1.40 p. m.	74	20.0	250
June 26, 1930	9.30 a. m.	73	17.0	1,440

C.—SIEVE ANALYSIS

Fraction	Weight	Percentage of dispersed sample
	Grams	
Retained on No. 10		0
Passing No. 10, retained on No. 20	0.98	2.13
Passing No. 20, retained on No. 40	0.80	1.74
Passing No. 40, retained on No. 60	0.90	1.96
Passing No. 60, retained on No. 140	4.32	9.39
Passing No. 140, retained on No. 200	3.80	8.26

[1] Volume of suspension, 1 liter.

1. On tracing paper placed over Figure 1, line 2 is constructed by the method previously described, for a specific gravity, G, of 2.85, a weight of dry soil dispersed, W, of 46.0 grams, and a temperature of suspension of 75° F., as indicated in Tables 7, A and 7, B. While some of the temperatures listed in Table 7, B vary slightly from 75° F., the temperature throughout the test may be assumed as being 75° F.

2. The percentages of material retained on each of the sieves in the sieve analysis are computed and listed in Table 7, C. From these data the percentage of material smaller than each of the sieve sizes is computed and recorded in the last column of Table 8.

3. On a piece of tracing paper placed over Figure 2 a curve of time against hydrometer reading is plotted, as shown by the broken line in Figure 2, from the observed data as recorded in Table 7, B. The intersections of this curve with the grain-diameter curves give the hydrometer readings corresponding to the times of sedimentation indicative of the grain sizes represented by the grain-diameter curves, uncorrected for variation of the specific gravity of the soil particles in suspension and the temperature of the suspension from the standard values, 2.65 and 67° F., respectively.

4. The tracing paper is shifted horizontally through a distance equal to the algebraic sum of the temperature and specific gravity corrections, which in this case, for a temperature of 75° F. and a specific gravity of 2.85, is to the right. It should be noted that moving the tracing paper upon which the curve of time against hydrometer reading has been plotted produces the same effect as moving the grain-diameter curves in the opposite direction. It is for this reason that a point representing the algebraic sum of the specific gravity and temperature corrections, easily obtained by means of a pair of dividers, is laid off from the line of zero correction in the direction corresponding to the sign of that sum and the tracing paper moved until this point coincides with the line of zero correction.

This curve in its shifted position, shown as a full line in Figure 2, gives correctly the hydrometer readings corresponding to the grain sizes indicated by the grain-diameter curves.

5. The hydrometer readings corresponding to the percentages of material passing the No. 140 and the No. 200 sieves as recorded in Table 8 are obtained from line 2, Figure 1. In this case the values are 84.78 per cent and 76.52 per cent, respectively, and their computed hydrometer readings are 39.5 and 35.3. These hydrometer readings are plotted on the grain-diameter curves (fig. 2) corresponding to their respective sieve sizes with the tracing paper in its shifted position. These points are shown as points 1 and 2, Figure 2.

6. The two points are then connected with the curve previously drawn (full line, fig. 2) in order to tie in the results given by the sieve analysis with those given by the hydrometer analysis.

7. The hydrometer readings corresponding to the grain sizes tabulated in Table 8 are obtained from the curve (full line, fig. 2). Thus the hydrometer reading corresponding to a grain diameter of 0.05 millimeter is 32.0 and the hydrometer reading corresponding to a grain diameter of 0.002 millimeter is 19.3.

8. For these hydrometer readings the corresponding percentages of soil in suspension are obtained from line 2 (fig. 1). Thus a hydrometer reading of 32.0 indicates 69.3 per cent of soil in suspension and a hydrometer reading of 19.3 indicates 42.8 per cent of soil in suspension. These values are recorded in Table 8 and used in plotting the soil accumulation curve, which is shown in Figure 3. From this curve the percentage of soil smaller than any specific diameter may be obtained.

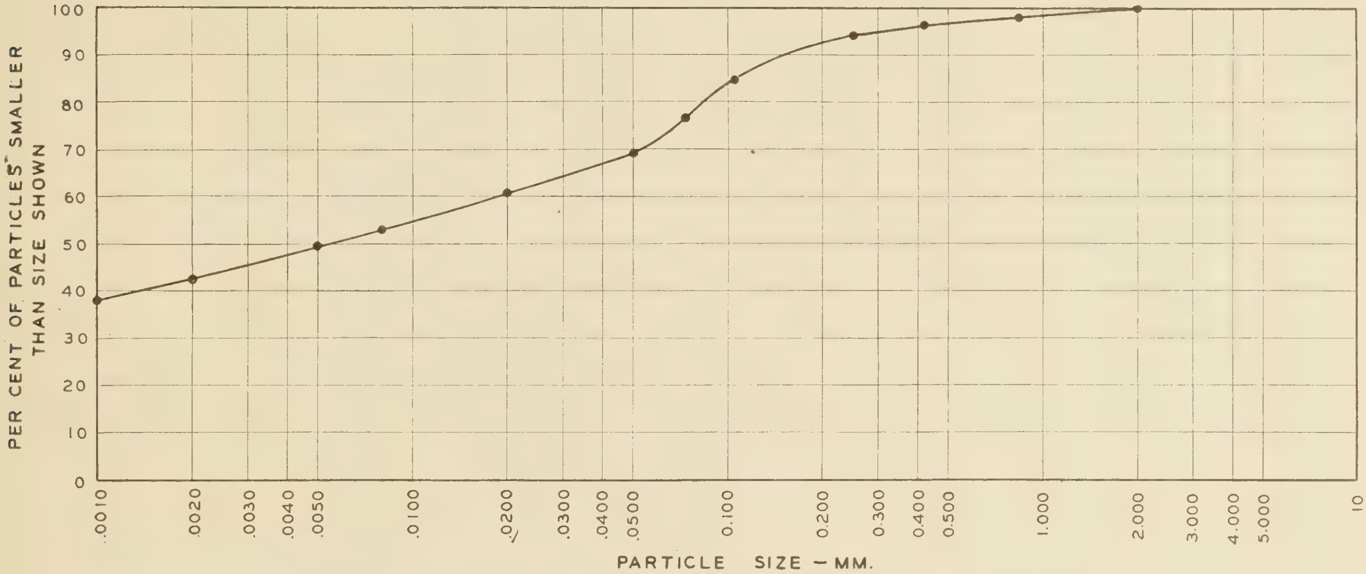

Figure 3.—Grain-size Accumulation Curve for Soil Sample 5,394X

Table 8.—*Grain-size accumulation data for soil sample 5,394X*

Sieve No.	Maximum grain size of fraction	Hydrometer reading	Percentage of total sample
	Millimeters	*Grams per liter*	
10	2.0		100.00
20	0.84		97.87
40	0.42		96.13
60	0.25		94.17
140	0.105	[1] 39.5	84.78
200	0.074	[1] 35.3	76.52
	0.05	32.0	69.3
	0.02	28.0	61.0
	0.008	24.4	53.4
	0.005	22.5	49.4
	0.002	19.3	42.8
	0.001	17.2	38.4

[1] Computed.

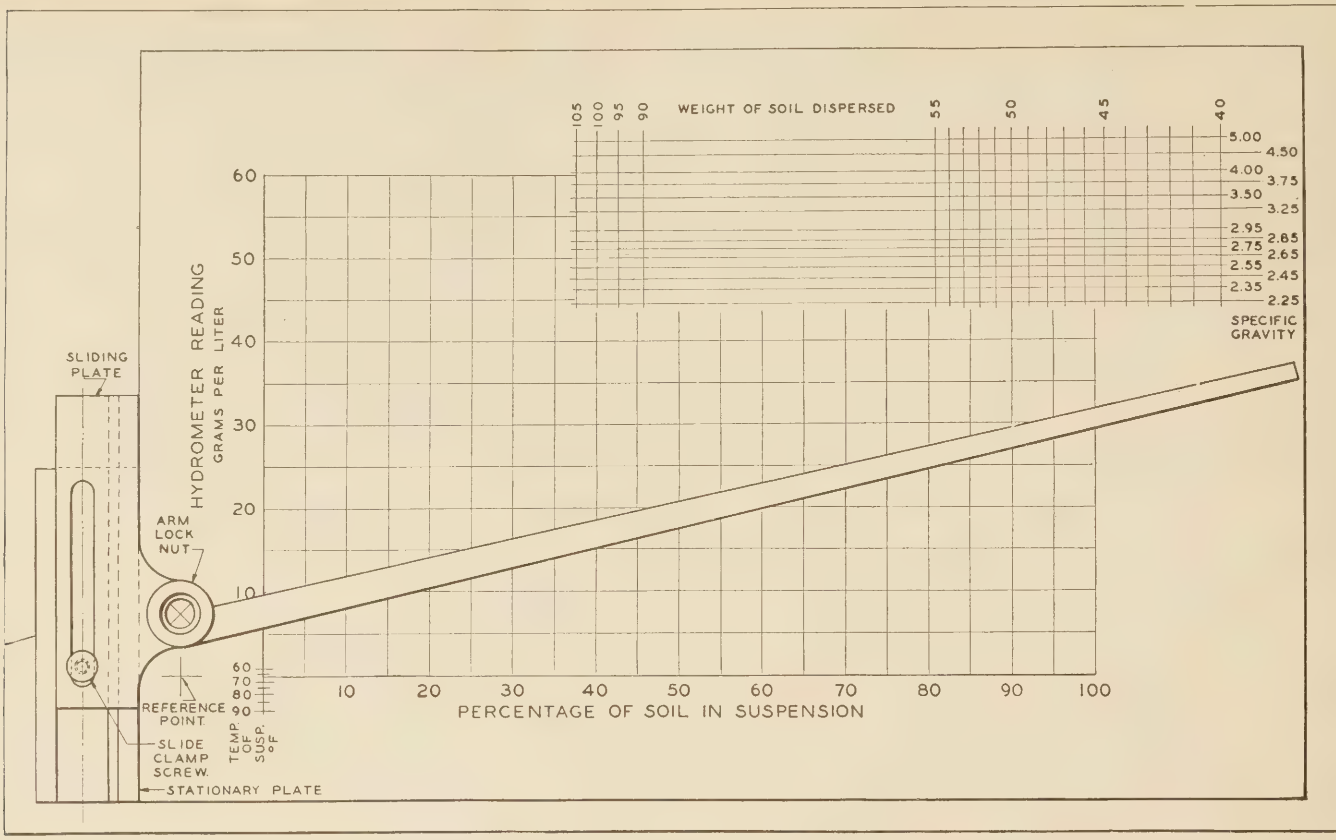

Figure 4.—Chart and Protractor for Converting Hydrometer Readings to Percentages of Originally Dispersed Soil Remaining in Suspension

SPECIAL APPARATUS ASSISTS IN PERFORMING THE GRAPHICAL SOLUTION

The foregoing procedure was described in detail in order to explain clearly the basis of the various operations. The procedure used in the laboratory of the Bureau of Public Roads is the same as that described above in essentials, but is somwhat simplified by the use of special apparatus.

The apparatus which assists in determining the relation between the hydrometer reading and the percentage of soil in suspension is shown in Figure 4. It consists of a chart containing scales similar to those shown in Figure 1 and an adjustable protractor which slides on a fixed base. Both the protractor and the chart are mounted on a drawing board 12 inches wide and 16 inches long.

The scales for hydrometer reading, percentage of soil in suspension, temperature, and specific gravity are constructed exactly like and in the same position as the same scales in Figure 1. A reference point for the fulcrum of the protractor arm is located 1 inch to the left of the origin. To compensate for this displacement, the scale for weight of soil dispersed is shifted 1 inch to the left of the position shown in Figure 1. This displacement was necessitated by the fact that if the reference point were at the origin the fulcrum of the protractor would interfere with reading the scales in the lower left-hand corner of the chart.

The protractor is operated in the following manner: The slide clamp screw is loosened and the protractor is moved vertically until the intersection of the cross hairs in the transparent center of the fulcrum of the protractor is directly over the reference point. The slide clamp screw is then tightened and the arm lock nut is loosened. The protractor arm is rotated until its reading edge passes through a point whose abscissa corresponds to the given weight of soil displaced and whose ordinate corresponds to the given specific gravity. The arm lock nut is then tightened, the slide clamp screw is loosened, and the protractor is moved vertically until the reading edge of the arm intersects the temperature scale at the desired point. The slide clamp screw is then tightened. In this position the reading edge of the protractor arm, corresponding in position to line 2 (fig. 1), will give correctly the percentage of soil particles in suspension indicated by the hydrometer readings.

The apparatus which assists in determining the grain size is illustrated in Figure 5. It consists of a chart similar to that shown in Figure 2, but without the temperature and specific gravity scales, and a sliding carriage which serves to shift the tracing paper, all mounted on a drawing board 16 by 21 inches in size. The tracing paper is held in the sliding carriage by two clamps. The sliding of the carriage is controlled by means of a thumbscrew and thrust yoke located at the upper right-hand corner of the board.

The specific gravity scale is scribed on the carriage exactly as it was plotted in Figure 2, and the temperature scale is scribed on a fixed metal guide adjacent to the specific gravity scale. The scale values are the same as were used in the construction of the temperature scale (fig. 2), but positive values are plotted to the left and negative values to the right of the zero correction line. This is necessary because the specific gravity scale moves with the tracing paper but the temperature scale remains fixed. The position of these scales on the apparatus is shown in Figure 5. The chart containing the grain-size curves is held in place on the drawing board by means of two clamps, as shown.

This apparatus is operated in the following manner: The tracing paper is inserted in the slot in the movable carriage provided for it and the clamps are tightened. By means of the adjusting screw the position of the described. The tracing paper is then displaced horizontally by moving the slide carriage until the two correction scales are in such a position that the given specific gravity coincides with the given temperature.

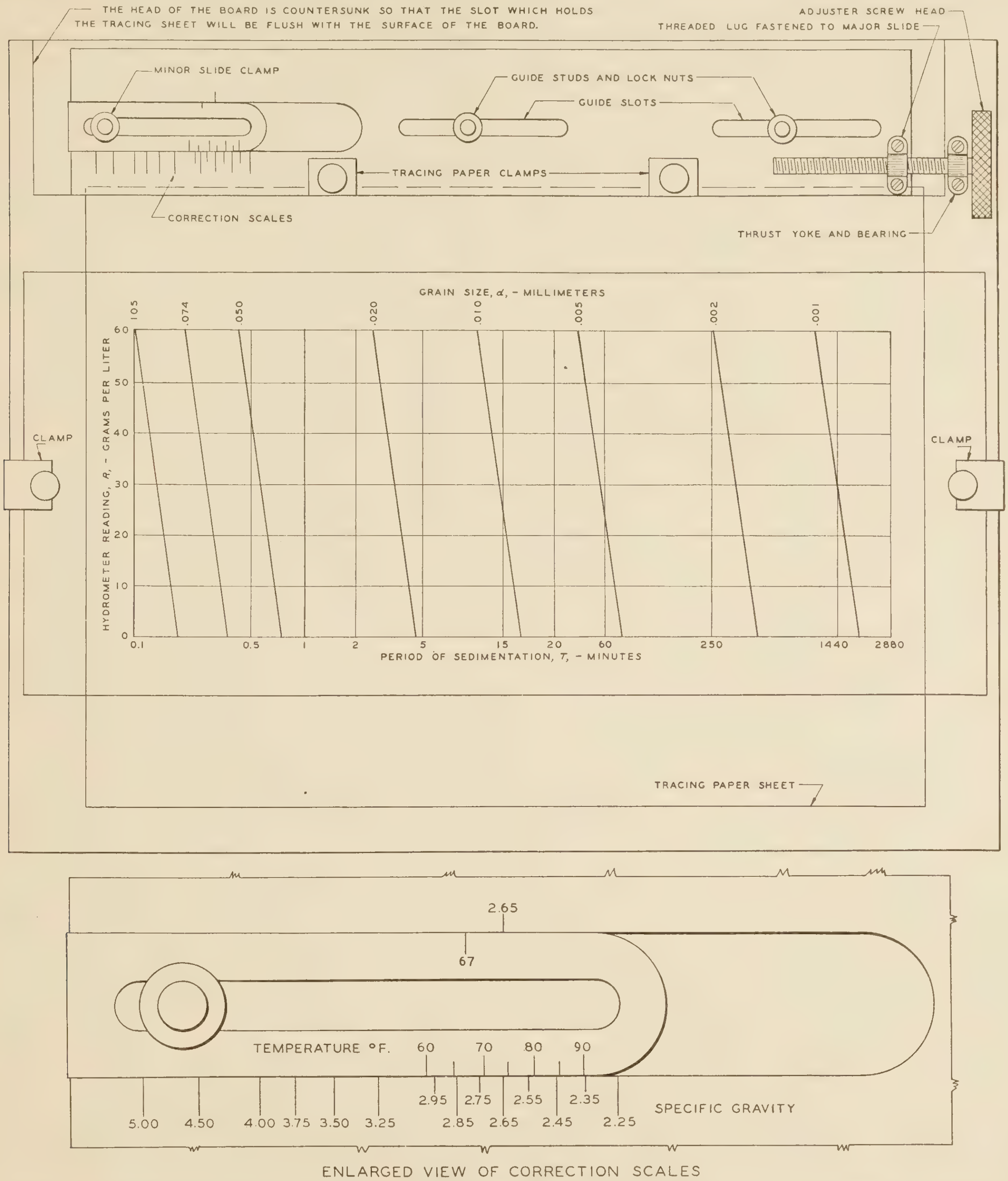

Figure 5.—Chart and Mechanical Device for Obtaining from Test Data the Hydrometer Readings Corresponding to Specific Grain Sizes

carriage is adjusted so that a specific gravity of 2.65 on the specific gravity scale coincides with a temperature of 67° F. on the temperature scale. A curve of time of sedimentation against hydrometer reading is plotted on the tracing paper in the manner previously The curve of time of sedimentation against hydrometer reading will then be in the correct position to give the hydrometer readings corresponding to the grain diameters for which the information is desired.

INVESTIGATION OF TAR ROADS IN PROGRESS

In cooperation with representatives of the tar industry, the Bureau of Public Roads is conducting an investigation of low cost and secondary roads on which tar was used in construction and maintenance. A committee of three was appointed to represent the producers of tar, and an engineer was assigned to work directly with members of the bureau staff in making the study. Work on the project was begun in the early part of this year.

Although tar has been used as a road material in different parts of the country for many years, it is of special interest at the present time to study its performance when used in low-cost road treatments. It is believed that the investigation which is now being carried on will produce valuable information regarding methods of construction and maintenance costs, and the behavior of tar-bound surfaces under light and medium traffic.

The procedure adopted involves (*a*) a preliminary survey of the type of road selected for study, and (*b*) a detailed study of a limited number of road projects. The preliminary survey serves to bring out the factors which should be given attention in the special study. Roads are selected which afford an opportunity to investigate all such factors.

The detailed study of each project involves a complete investigation of the methods employed in construction, the materials and proportions used, maintenance of the road, and its surface condition. Samples are taken to determine the thickness and condition of the mat. In addition to the field work, exhaustive laboratory tests are made on the materials composing the mat, as well as on the base materials and the subgrade. The study also includes an analysis of the costs of construction and maintenance. Information regarding the volume and character of the traffic, if not available from other sources, is obtained in the course of the field work.

Since the beginning of this investigation early in 1931, a survey has been made in North Carolina of sand-clay, topsoil, traffic-bound gravel, and stone roads, surface-treated with tar. Over 1,000 miles of such surfaces have been built in the past few years and an extensive program of surface treatment is now in progress. The survey has been completed and a report is now being prepared.

A second survey, covering tar-bound roads in Pennsylvania, is now under way. The preliminary survey has been completed and the detailed study begun. In addition to a study of low-cost surface treatments, the Pennsylvania work includes an investigation of tar-bound macadam construction. Surfaces of this type consist generally of a layer of aggregate 1¼ inches to 5/8 inch in size spread to a loose depth of about 3 inches, penetrated with a cold application of tar, and compacted by rolling or by traffic.

In the Pennsylvania study it will be possible to investigate old as well as new work, thereby obtaining information on the effect of changes in methods and materials over a period of years. Following the completion of the work in Pennsylvania it is planned to extend the investigation to different parts of the country, and to study other types of construction which have proved their worth and might with advantage come into wider use. Information of value derived from these studies will be published in the form of progress reports as rapidly as possible.

TRAFFIC SURVEY OF WASHINGTON, D. C., AREA BEGUN

On September 10, 1931, the Bureau of Public Roads, in cooperation with other agencies, inaugurated a survey of traffic on the principal highways in the area immediately adjacent to Washington, D. C. The cooperating agencies are the National Capital Park and Planning Commission, the District of Columbia, the Maryland State Roads Commission, the Virginia Department of Highways, the Maryland National Capital Park and Planning Commission, the City of Alexandria, Arlington and Fairfax Counties, Virginia; and Prince Georges and Montgomery Counties, Maryland.

This is the first comprehensive survey of the area surrounding the city of Washington. It is expected to yield information essential to the solution of traffic problems in this region. The general purpose of the survey, according to the agreement signed by the cooperating agencies, is "to secure facts and obtain information which will enable the agencies concerned to develop a comprehensive, systematic, and connected system of main highways within and between the areas of Fairfax and Arlington Counties, Va.; the city of Alexandria, Va.; Montgomery and Prince Georges Counties, Md.; and the District of Columbia, including a study of proper connections with the Federal-aid highway systems of Maryland and Virginia within these areas, and such other adjacent areas as may be affected by a general highway plan for the environment of the District of Columbia. The surveys will be directed toward the development of a priority program of highway construction and betterment in the entire area and toward fixing the location and connections of suitable belt lines, relief roads, or necessary relocations and extensions of existing highways. They will include a highway traffic census to determine the origin and destination of various kinds of vehicles, the preparation of a comprehensive report, and an analysis of the information obtained, for the guidance of the officials concerned in the various jurisdictions."

INDEX TO VOLUME 10 OF PUBLIC ROADS AVAILABLE

An index to volume 10 of Public Roads, which includes the issues from March, 1929, to February, 1930, is now available for distribution, and copies may be obtained without charge from the Bureau of Public Roads, United States Department of Agriculture, Washington, D. C. Indexes to volumes 6, 7, 8, and 9 have previously been published, and a supply of these indexes is still on hand. The index to volume 11 is now being prepared.

○

ROAD PUBLICATIONS OF BUREAU OF PUBLIC ROADS

Applicants are urgently requested to ask only for those publications in which they are particularly interested. The Department can not undertake to supply complete sets nor to send free more than one copy of any publication to any one person. The editions of some of the publications are necessarily limited, and when the Department's free supply is exhausted and no funds are available for procuring additional copies, applicants are referred to the Superintendent of Documents, Government Printing Office, this city, who has them for sale at a nominal price, under the law of January 12, 1895. Those publications in this list, the Department supply of which is exhausted, can only be secured by purchase from the Superintendent of Documents, who is not authorized to furnish publications free.

ANNUAL REPORTS

Report of the Chief of the Bureau of Public Roads, 1924.
Report of the Chief of the Bureau of Public Roads, 1925.
Report of the Chief of the Bureau of Public Roads, 1927.
Report of the Chief of the Bureau of Public Roads, 1928.
Report of the Chief of the Bureau of Public Roads, 1929.
Report of the Chief of the Bureau of Public Roads, 1930.

DEPARTMENT BULLETINS

No. *136D Highway Bonds. 20c.

*347D. Methods for the Determination of the Physical Properties of Road-Building Rock. 10c.

*532D. The Expansion and Contraction of Concrete and Concrete Roads. 10c.

*583D. Reports on Experimental Convict Road Camp, Fulton County, Ga. 25c.

*660D. Highway Cost Keeping. 10c.

1279D. Rural Highway Mileage, Income, and Expenditures 1921 and 1922.

1486D. Highway Bridge Location.

DEPARTMENT CIRCULAR

No. 331C. Standard Specifications for Corrugated Metal Pipe Culverts.

TECHNICAL BULLETIN

No. 55T. Highway Bridge Surveys.

SEPARATE REPRINT FROM THE YEARBOOK

No. 1036Y. Road Work on Farm Outlets Needs Skill and Right Equipment.

MISCELLANEOUS CIRCULARS

No. 62M. Standards Governing Plans, Specifications, Contract Forms, and Estimates for Federal-Aid Highway Projects.

*93M. Direct Production Costs of Broken Stone. 25c.

109M. Federal Legislation and Regulations Relating to the Improvement of Federal-Aid Roads and National-Forest Roads and Trails, Flood Relief, and Miscellaneous Matters.

MISCELLANEOUS PUBLICATION

No. 76MP. The Results of Physical Tests of Road-Building Rock.

TRANSPORTATION SURVEY REPORTS

Report of a Survey of Transportation on the State Highway System of Ohio. (1927)

Report of a Survey of Transportation on the State Highways of Vermont. (1927)

Report of a Survey of Transportation on the State Highways of New Hampshire. (1927)

Report of a Plan of Highway Improvement in the Regional Area of Cleveland, Ohio. (1928)

Report of a Survey of Transportation on the State Highways of Pennsylvania. (1928)

REPRINTS FROM THE JOURNAL OF AGRICULTURAL RESEARCH

Vol. 5, No. 17, D- 2. Effect of Controllable Variables upon the Penetration Test for Asphalts and Asphalt Cements.

Vol. 5, No. 19, D- 3. Relation Between Properties of Hardness and Toughness of Road-Building Rock.

Vol. 5, No. 24, D- 6. A New Penetration Needle for Use in Testing Bituminous Materials.

Vol. 11, No. 10, D-15. Tests of a Large-Sized Reinforced-Concrete Slab Subjected to Eccentric Concentrated Loads.

* Department supply exhausted.

UNITED STATES DEPARTMENT OF AGRICULTURE

BUREAU OF PUBLIC ROADS

CURRENT STATUS OF FEDERAL-AID ROAD CONSTRUCTION

AS OF

SEPTEMBER 30, 1931

STATE	COMPLETED MILEAGE	UNDER CONSTRUCTION					APPROVED FOR CONSTRUCTION					BALANCE OF FEDERAL AID FUNDS AVAILABLE FOR NEW PROJECTS	STATE
		Estimated total cost	Federal aid allotted	MILEAGE			Estimated total cost	Federal aid allotted	MILEAGE				
				Initial	Stage[1]	Total			Initial	Stage[1]	Total		
Alabama	2,274.1	3,977,720.41	1,975,776.79	158.6	36.4	195.0						3,328,206.05	Alabama
Arizona	913.9	5,308,952.41	3,652,791.85	230.0	189.2	419.2						311,214.52	Arizona
Arkansas	1,859.1	5,341,014.54	2,793,272.77	121.7	96.9	218.6	506,930.89	253,465.43	19.6	4.9	24.5	109,241.63	Arkansas
California	1,995.3	12,179,922.30	5,267,802.87	316.9	101.3	418.2	1,227,415.38	219,892.50	41.3		41.3	299,698.19	California
Colorado	1,361.1	7,370,115.99	3,918,400.78	312.7	92.1	404.8	849,448.61	384,260.11	31.8	9.4	41.2	493,223.26	Colorado
Connecticut	268.3	4,591,129.06	1,693,759.63	43.0		43.0							Connecticut
Delaware	323.9	928,942.00	463,716.50	42.1		42.1						39,994.21	Delaware
Florida	554.4	6,161,508.65	2,872,456.15	174.4		174.4						1,609,098.91	Florida
Georgia	2,868.2	8,859,090.98	4,172,237.29	255.1	151.9	407.0	1,666,425.08	613,501.89	29.3	35.5	64.8	93,579.39	Georgia
Idaho	1,344.6	3,581,620.31	2,046,594.97	232.2	74.7	306.9	408,363.79	202,206.15	13.0	12.8	25.8	198,110.41	Idaho
Illinois	2,397.8	25,858,345.54	12,008,686.52	782.5	31.9	814.4	4,675,237.47	1,978,513.89	152.5	4.6	157.1		Illinois
Indiana	1,597.4	11,681,398.77	5,766,524.14	371.7		371.7	698,282.70	349,140.34	38.3		38.3	416,716.87	Indiana
Iowa	3,229.6	5,107,575.34	2,007,337.70	93.5	69.5	163.0						15,205.91	Iowa
Kansas	3,432.9	6,096,166.17	2,908,115.71	356.6	36.0	392.6	40,717.03	18,414.02	3.4		3.4	161,096.64	Kansas
Kentucky	1,646.8	5,261,246.41	2,421,400.07	293.1	69.9	363.0	195,744.32	94,502.33	3.9	5.8	9.7	38,946.75	Kentucky
Louisiana	1,455.0	7,899,135.56	3,675,142.63	188.6	20.3	208.9	2,567,840.55	135,581.56	1.0		1.0	57,860.55	Louisiana
Maine	651.4	3,716,389.99	1,535,875.48	82.2		82.2	474,329.91	213,859.88	3.9		3.9	325,509.16	Maine
Maryland	740.1	1,198,056.70	512,236.52	40.7		40.7	49,918.00	24,959.00	2.7		2.7	30,887.35	Maryland
Massachusetts	736.4	11,230,074.71	3,224,991.50	97.4		97.4	1,449,468.21	561,989.51	13.3		13.3	430,185.38	Massachusetts
Michigan	1,826.6	11,924,482.85	5,183,141.46	395.4	50.3	445.7	248,466.96	123,275.00	13.1		13.1	1,368,527.77	Michigan
Minnesota	3,956.1	8,465,081.03	3,701,797.71	79.0	317.7	396.7	154,382.24	33,028.32	.9	1.2	2.1	14,252.31	Minnesota
Mississippi	1,764.8	4,349,611.86	2,134,938.38	184.3	88.0	272.3	242,383.87	119,760.39		12.6	12.6	3,693,928.90	Mississippi
Missouri	2,754.9	7,488,442.65	3,121,381.06	234.7	34.6	269.3						162,198.26	Missouri
Montana	2,190.8	10,003,739.65	5,616,401.77	644.0	115.5	759.5	609,999.78	341,636.02	59.5	33.4	92.9	1,047,978.39	Montana
Nebraska	3,913.1	9,913,671.70	4,617,451.98	299.1	203.0	502.1	255,703.05	127,851.50	27.0	28.4	55.4	410,995.70	Nebraska
Nevada	1,094.6	3,262,391.58	2,138,387.70	108.6	263.9	372.5	4,951.87	4,399.73		.5	.5	197,354.49	Nevada
New Hampshire	393.9	1,584,270.81	568,311.17	32.2	7.2	39.4							New Hampshire
New Jersey	574.2	5,378,968.28	1,896,751.43	62.0	.3	62.3	1,398,428.28	538,623.71	5.6	.5	6.1	194,826.21	New Jersey
New Mexico	2,158.9	2,986,906.05	1,918,542.91	90.9	75.3	166.2	107,277.63	67,700.35	.3		.3	125,621.09	New Mexico
New York	2,764.6	37,196,891.40	13,938,669.98	725.3	7.0	732.3	1,595,300.00	560,450.00	26.2		26.2	279,475.24	New York
North Carolina	2,148.6	3,114,668.75	1,511,179.36	89.0	17.4	106.4	334,529.01	167,214.48	16.5	15.4	31.9	1,469,519.39	North Carolina
North Dakota	4,836.9	2,719,314.00	1,357,433.85	317.2	254.4	571.6	629,477.13	334,060.22	31.0	184.8	215.8	720,443.91	North Dakota
Ohio	2,613.0	16,092,046.81	5,666,137.42	278.0	39.2	317.2	1,645,404.97	605,101.03	33.6	5.7	39.3	412,305.61	Ohio
Oklahoma	2,036.0	7,103,270.25	3,631,930.70	246.6	127.6	374.2	601,125.31	157,257.22	25.5	4.0	29.5	16,649.85	Oklahoma
Oregon	1,379.3	6,053,783.66	3,386,428.56	223.1	50.1	273.2	147,885.65	88,871.50	13.3		13.3	361,504.59	Oregon
Pennsylvania	2,817.7	10,900,013.33	4,681,763.22	240.4		240.4	15,163.78	7,040.14	.1		.1	457,715.24	Pennsylvania
Rhode Island	249.4	755,371.45	293,691.92	8.2		8.2	37,587.29	18,793.64	.1		.1	160,101.56	Rhode Island
South Carolina	1,883.9	4,850,633.05	2,157,898.52	78.2	122.3	200.5	587,639.45	150,042.23	19.7	9.0	28.7	100.50	South Carolina
South Dakota	3,913.1	4,254,340.36	2,240,765.21	226.0	243.0	469.0	65,501.32	35,061.21	.6	10.0	10.6	22,796.13	South Dakota
Tennessee	1,665.3	610,739.89	301,317.46	8.5		8.5						2,026,820.81	Tennessee
Texas	7,156.4	18,151,754.17	8,916,457.32	762.8	287.5	1,050.3	3,354,559.10	1,421,422.33	181.5	44.3	225.8	1,737,037.59	Texas
Utah	1,174.7	1,129,554.05	629,522.38	54.6	16.4	71.0	417,076.93	292,465.40	26.5	13.7	40.2	255,181.73	Utah
Vermont	303.8	1,335,410.39	536,957.67	34.9	4.7	39.6						8,133.69	Vermont
Virginia	1,717.7	4,376,715.08	2,030,600.67	198.3	25.8	224.1	1,062,329.16	527,151.20	50.1		50.1	181,577.01	Virginia
Washington	1,020.2	5,634,594.75	2,476,358.47	164.4	39.7	204.1	743,149.65	265,600.00	24.6		24.6	547,590.20	Washington
West Virginia	777.7	5,189,650.64	2,203,247.03	134.5	22.0	156.5	225,073.78	104,726.24	5.5		5.5	94,288.56	West Virginia
Wisconsin	2,460.4	8,378,010.98	3,348,706.43	266.0	84.4	350.4	285,044.61	90,909.97	10.8	.6	11.4	12,692.50	Wisconsin
Wyoming	1,817.3	3,460,525.90	1,922,106.77	247.1	187.8	434.9	39,799.12	26,128.12	8.7		8.7	72,545.77	Wyoming
Hawaii	57.8	1,058,807.25	463,088.90	33.0		33.0	160,999.13	62,206.07	1.7		1.7	1,506,890.40	Hawaii
TOTALS	93,072.0	344,072,068.45	155,508,487.28	10,659.3	3,655.2	14,314.5	29,779,361.01	11,321,052.63	936.4	437.1	1,373.5	25,517,828.57	TOTALS

[1] The term stage construction refers to additional work done on projects previously improved with Federal aid. In general, such additional work consists of the construction of a surface of higher type than was provided in the initial improvement.

U. S. GOVERNMENT PRINTING OFFICE: 1931